ArkDSS Task 1, Spatial System Integration Component
Subtask 1.3, Historical Irrigated Acreage Snapshots

Prepared for:

Colorado Water Conservation Board
and
Colorado Division of Water Resources

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May 10, 2019

Contract No. CT2018-00578, ArkDSS Spatial System Integration Component

HRS Job No. 99001-63

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1.0 INTRODUCTION

This report documents the approach used to create the geographic information system (GIS) data associated with Subtask 1.3, Historical Irrigated Acreage Snapshots, under Task 1, Spatial System Integration Component, of the Arkansas River Decision Support System (ArkDSS). This report and the related GIS deliverables were prepared by HRS Water Consultants, Inc. (HRS) and ElephantFish LLC (EF).

The goals of Subtask 1.3 were to:

- create irrigated parcel datasets, or irrigated acreage "snapshots", for Division 2 for the snapshot years 1998, 1988, 1975, and 1954,
- describe each parcel's water supply and irrigation type for each snapshot year, and
- describe the crop type for each parcel in snapshot years 1998 and 1988.

The historic irrigated parcel datasets were created in ArcGIS™ Desktop[1] by starting with a "master" irrigated parcel dataset[2] from irrigation year 2010, provided by the State Engineers Office (SEO) and Division 2, then working backwards in time, starting with snapshot year 1998. Other data including aerial imagery, ditch traces, historical maps, satellite imagery, well locations, and ditch diversion records were also used in creating the parcel datasets. The irrigated parcel datasets documented in detail in this report are provided in GIS format (geodatabase) and comprise the major deliverable of the Task 1 Spatial System Integration Component.

Irrigated status[3] for each parcel in snapshot years 1998 and 1988 was determined using the Normalized Difference Vegetation Index maximum (NDVImax) from satellite imagery, provided by the SEO, using a season-wide and basin-wide NDVI threshold. Irrigated status for each parcel in snapshot years 1975 and 1954 was determined using a combination of aerial imagery and ditch diversion records. The water supply unique identifier, (i.e. either a surface water and/or groundwater WDID) for each parcel was copied from the later year dataset to the earlier year dataset, unless records indicated otherwise.

The crop type of each irrigated parcel for snapshot years 1998 and 1988 was determined by using either a time-series NDVI 'reference curve' (described in detail in Section 5) or by querying parcel elevation and classifying the parcel crop type based on center pivot/non-pivot fields. The latter method was used in higher elevation areas where only alfalfa and grass pasture are typically grown. The crop type of each irrigated parcel for snapshot year 1975 was determined by spatially joining parcel centroids and associated crop type information from 1988 to the 1975 irrigated parcels. Then, the crop type for each 1954 irrigated parcel was determined by spatially joining parcel centroids and associated crop type information from 1975 to the 1954 irrigated parcels.

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[1] The use of trade names does not represent or imply an endorsement.

[2] 2010 Irrigated Parcel GIS coverage provided to HRS by CDWR in August 2017.

[3] 'Irrigated status' for each parcel was assigned to be either irrigated or non-irrigated.

This report includes numerous maps, figures, and graphs that help to visually tell the story of how the irrigated parcel datasets were developed. In instances where very specific, yet important pieces of information need to be conveyed about the data, this information has been listed inside a blue text box. The report is divided into six main sections including: digitization approach, irrigated parcel attribute table adjustments, quality control checks, crop type assignment, data considerations, and data deliverables.

2.0 DIGITIZATION APPROACH

The general approach used to develop the irrigated parcel datasets for snapshot years 1998, 1988, 1975, and 1954 consists of these steps:

1. Beginning with the 2010 irrigated parcel dataset[4] (the master parcel dataset), digitize or adjust potentially irrigated parcel boundaries based on parcel extents assessed in aerial imagery for each snapshot year
2. Classify each parcel as either irrigated or non-irrigated using either the NDVImax raster dataset (for post-1985 snapshots) or a combination of aerial imagery and diversion records (pre-1985 snapshots)

2.1 Snapshot Years

The snapshot years, 1998, 1988, 1975, 1954, were collaboratively selected by the CWCB, CDWR, HRS, and Digital Data Services (DDS)[5] based on availability of historic aerial imagery, climatic conditions, and benefit to the ArkDSS model. Even though the irrigated parcel datasets are referred to by a single year, they do not necessarily represent only that year. The following list describes the actual timeframes of each snapshot year:

- Snapshot 1998:
    - The 1998 snapshot is also representative of 1999 in portions of Division 2 due to the unavailability of 1998 imagery in those areas.
    - The majority of the parcels are in areas where 1998 imagery was available with most of those parcels falling within the Hydrologic-Institutional Model (HIM) area.
    - In areas where only 1999 imagery was available, the 1999 NDVImax and 1999 individual NDVI images and county crop statistics were used to determine irrigated status and crop type.

[5] DDS completed historic air photo acquisition and georeferencing of the air photos used as base maps in digitizing the irrigated snapshot parcels. See Task Memorandum 1.2 for more details.

    - In areas where only 1998 imagery was available, the 1998 NDVImax and 1998 individual NDVI images and county crop statistics were used to determine irrigated status and crop type.
- Snapshot 1988:
    - Since imagery from 1988 was available for the entire Division where irrigated parcels historically exist with minor exceptions in Districts 11, 67, and the northern portion of 17, the 1988 snapshot is representative of only 1988. Imagery acquired during either 1989, 1991, or 1993 were used in those areas where 1988 imagery was not available.
- Snapshots 1975 and 1954:
    - Most of the imagery for the 1954 snapshot was acquired during 1954 with some exceptions in Districts 10, 11, 13, 14, 15, and 79. Images acquired during 1953 or 1955 fill in these areas where 1954 imagery was not available.
    - Similarly, most of the imagery for the 1975 snapshot was acquired during 1975 with some exceptions in Districts 12, 13, 16, 79, and the northern portion of 17 and 67. Images acquired during 1974, 1977, and 1979 fill in these areas where 1975 imagery was not available.
    - A collaborative decision between the SEO, Wilson Water Group (WWG), and the Colorado Decision Support System (DSS) team was made that these earlier snapshots should represent a "period" rather than a specific year for the irrigated parcels. Therefore,
        - Snapshot 1975 represents the period of 1965 – 1979; and
        - Snapshot 1954 represents the period of 1950 – 1964. However,
        - Wells that are assigned to parcels for the early snapshots represent the snapshot year only, not the entire period. This is discussed in Section 3.3.

2.2 Digitize/Adjust Potentially Irrigated Parcel Boundaries

All digitization was completed using ESRI's ArcGIS desktop software and began with the 2010 irrigated parcel dataset developed by the SEO with input from WWG and Division 2 water commissioners and is referred to as the master parcel dataset herein. Due to the large spatial extent and diversity of the irrigated parcels within the master parcel dataset a "divide and conquer" approach was taken. First, the master parcel dataset was divided into two datasets: (1) those parcels that are within the HIM extent; and, (2) those parcels that fall outside of the HIM extent. The master parcel dataset consisted of 16,204 individual parcels densely spaced within or near the valley fill aquifer of the HIM. The non-HIM parcels, consisting of approximately 8,600 individual parcels, were further divided by Division 2 water districts since it was anticipated that decisions, challenges, and irrigation history would be somewhat unique within each district. Figure 1 displays the extent and density of the master parcel dataset.

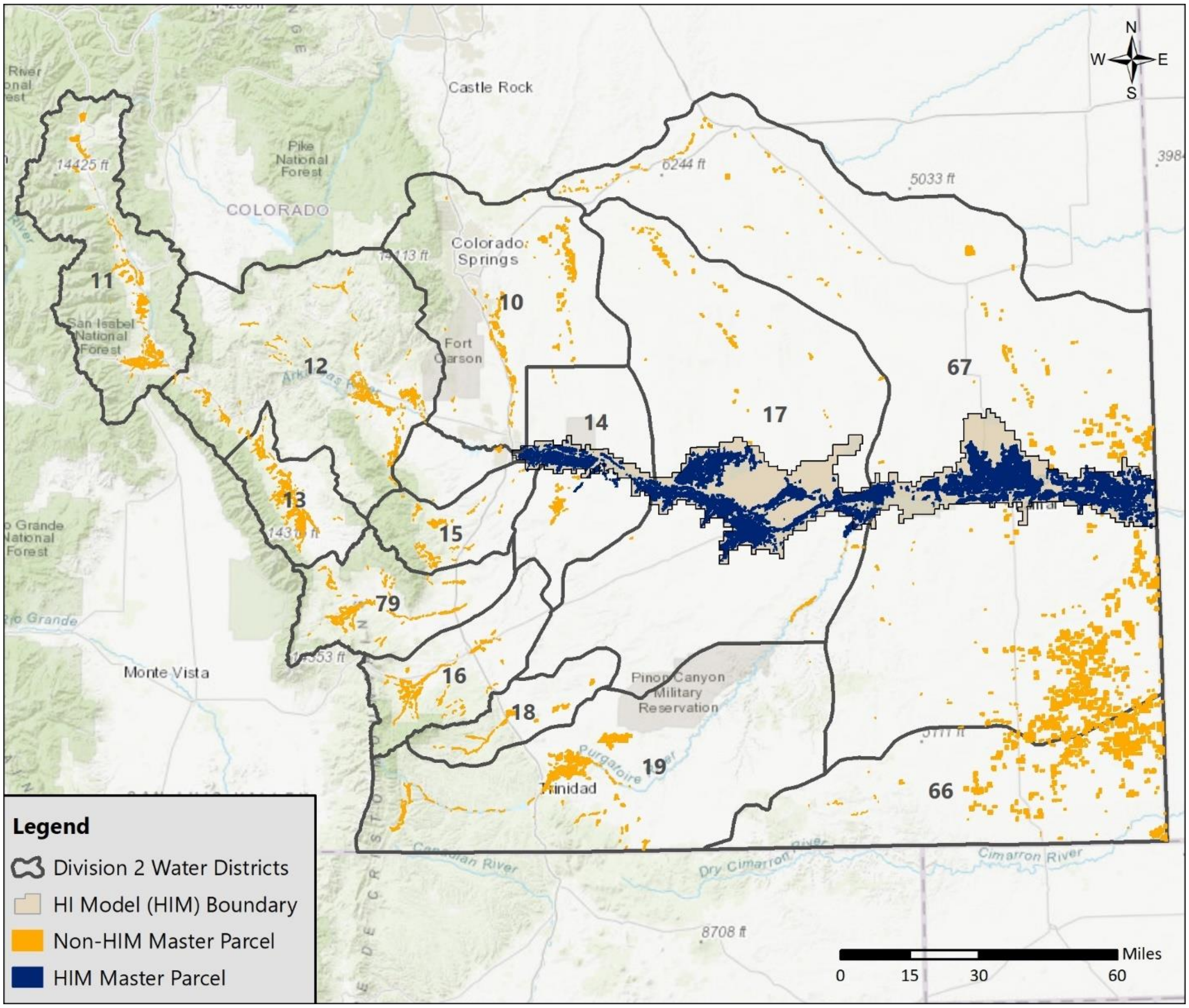


Figure 1 – Extent and density of the master parcel dataset.

Three primary sources of data were used to assist in the digitization of the historic parcel datasets. These sources are:

- **Historic Imagery**
  - Historic imagery from each snapshot year was compiled under Subtask 1.2 – Historical Aerial photos. Detailed information regarding imagery collection and georeferencing methods are in the Subtask 1.2 memo.
- **Ditch/Canal Extents**
  - The ditch/canal extents were digitized and compiled per Subtask 1.1.A - Irrigation Canal Mapping. More detailed information regarding the digitization and compilation process are in the Subtask 1.1.A memo.

- **NDVImax Raster Dataset** (for post-1985 snapshot years only)
    - The NDVImax raster dataset was submitted to HRS by the SEO and was compiled by the following general method as previously outlined in "ArkDSS Memorandum, Phase 1 – Development of 2010 Irrigated Parcel Dataset, Subtask 1.2.1 Draft" (K. Thompson, CDWR, 08/26/2016):
        - "*The normalized difference vegetation index (NDVI) is used extensively to characterize the density of healthy vegetative biomass. From Landsat 5 satellite imagery, NDVI is calculated as (NIR – Red/NIR+Red). As a normalized ratio, NDVI values vary between -1 and 1. This range is often converted to a range of 0 to 200 to be able to store in a typical 8-bit raster image. Therefore, in an 8-bit image, an NDVI of 0.0 and 0.5 would have converted values of 100 and 150, respectively. The normalized NDVI image was processed for each of the individual satellite images (for that snapshot year). All of these individual NDVI images were overlain such that the resulting value at each pixel location represented the maximum NDVI value from all the individual NDVI images at that location. The resulting "maximum-NDVI" image is representative of the maximum amount of healthy vegetative biomass observed through the growing season at that location. The distribution of the "maximum-NDVI" image values within a parcel boundary for potentially irrigated field provides a measure of the "greenest" that field may have been during the growing season.*"
    - A season-wide and basin-wide threshold value of 150 was used to differentiate irrigated parcels (NDVImax >150) from non-irrigated parcels (NDVImax <150)

The steps we followed to update and digitize the parcel and field extents of the master parcel dataset going back in time through the snapshot years consisted of:

- Copying the master parcel dataset and saving it as the previous snapshot year.
- Working through the dataset parcel by parcel and comparing parcel boundary extents to the imagery of that snapshot year;
- Updating parcel extents as necessary;
- Comparing the parcel extents to the NDVImax raster dataset to determine if a parcel should be split where a portion may have been irrigated and another not irrigated;
- Exploring imagery adjacent to existing parcels for any new parcels that may need to be digitized for that snapshot year; and
- Repeating for the next previous snapshot year.

Digitization guidelines established through meetings with the CWCB and CDWR as well as internal meetings included:

- If a parcel is digitized in the master parcel dataset and appears to be irrigated in the imagery, check boundary extent and update, if necessary.
- If a parcel appears to be irrigated in the imagery and is not digitized in the master parcel dataset, then digitize it and assign it to the adjacent WDID, if obvious. If not obvious, leave water source blank.

- If a parcel does not appear to be irrigated in the imagery, but is included in the master parcel dataset already, then leave as is. It will most likely be assigned as "Not Irrigated" during the irrigation status process.
- Do not include major roads, buildings, wide waterways, or other man-made features in parcel extents.
- Split the parcel between portions of fields where different crop types are growing, if applicable.
- Split the parcel where the NDVImax shows a change from irrigated to non-irrigated within the same field, if applicable.
- Keep water source attached to parcel even if parcel is split and/or cut.
- Noticeable changes in boundary extents are to be updated; however, small inaccuracies found between the parcel extent and imagery are not to be updated.
    - Some of the small inaccuracies may be due to differences in georeferencing of the historic imagery. In these cases, parcels are not to be shifted to account for the georeferencing differences between snapshot years.
- Only merge parcels together where the field appears to have the same crop type in the aerial image that have the same water source (i.e. either same surface water or groundwater WDID).

Figure 2 shows an example of the basic concepts described above within a relatively small area in the HIM extent using 1988 snapshot data. The goal of the meetings in advance of starting the parcel digitizing process was to establish a set of consistent guidelines for the group of four HRS/EF staff members that completed in the digitizing. More detailed information regarding decision-making, challenges, and special cases within the water districts and HIM area are described below.

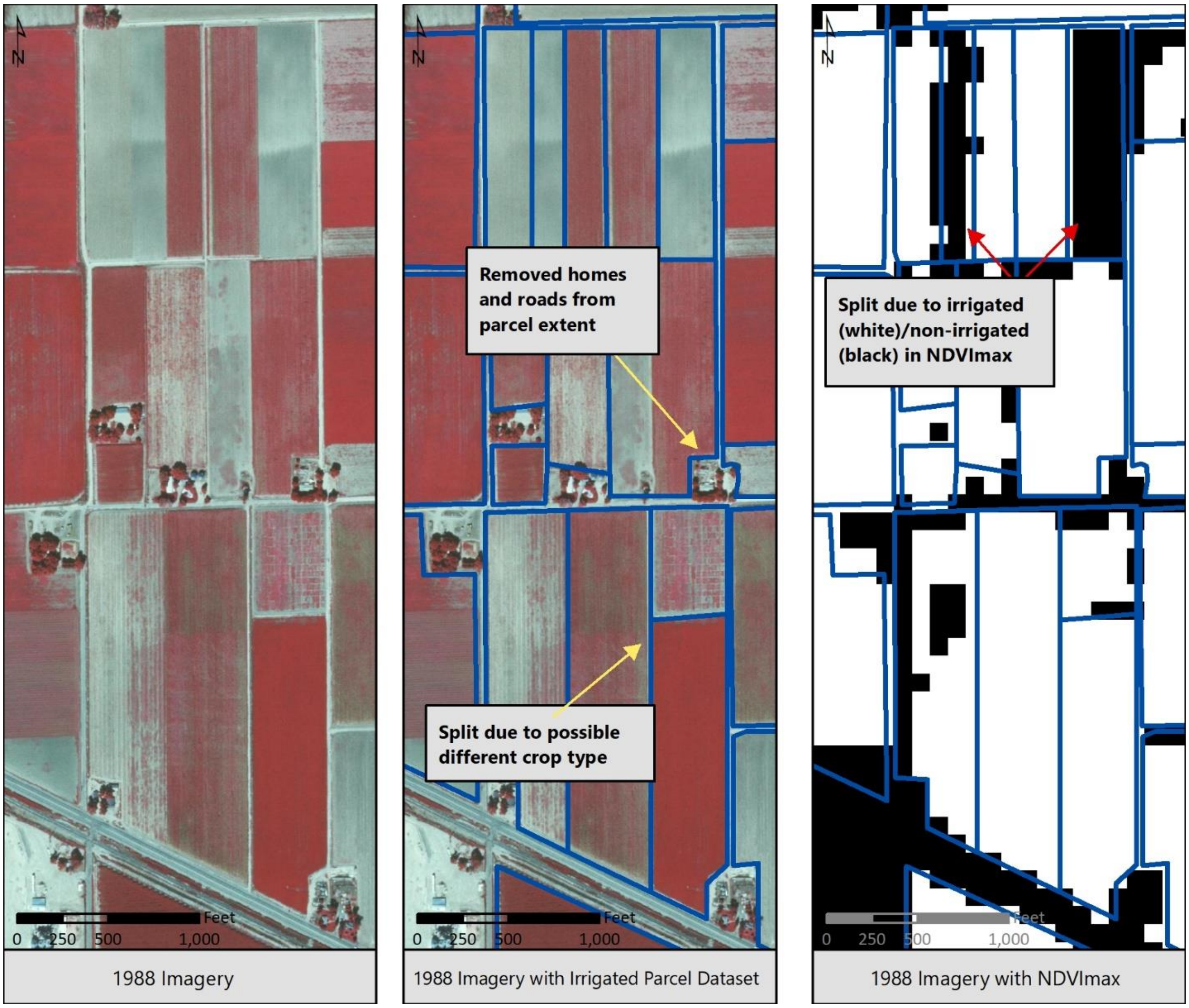


Figure 2 – Basic concept of digitizing parcel extents as outlined in the text above. Area shown is within the HIM extent using the 1988 snapshot parcels, imagery, and NDVImax raster dataset (gray or black NDVImax color = not irrigated).

2.2.1 Decision-Making for Area Inside the HIM

The HIM area is unique in that the individual irrigated parcels are relatively small in area in comparison to parcels found outside of the HIM area, and are densely spaced over an area extending approximately 138 miles along the Arkansas River. Overall, the land is irrigated by expansive ditches and/or private wells, with parcel size ranging from as large as 450 acres to less than 0.5 acre. The original extents of individual parcels within the master parcel dataset were clipped to exclude areas such as large roads, homes, and wide ditches, and were split where crop types appeared to differ within a single field. This convention was followed while digitizing the parcel boundaries going back in time through the snapshots. However, one significant update was made going back in time through the snapshots involving the topology, or spatial relationship, between individual parcels across minor (i.e. very narrow) geographic features such as small ditches, vegetated areas such as wind breaks, or between different crop types in a field. While going back in time to earlier snapshot years, individual parcels irrigated under the same ditch and/or well were merged together, then re-cut or split. This was done to 1) remove unnecessary space between parcels; 2) make it much more efficient in GIS to update the now coincident parcel boundaries through all four snapshots; and, 3) create a clean, accurate historic dataset. Although tedious for the first completed snapshot (1998), it greatly increased digitizing efficiency for the other three snapshots. Figures 3-5 display the general process taken to refine the topology of HIM area parcels for 3 different scenarios.

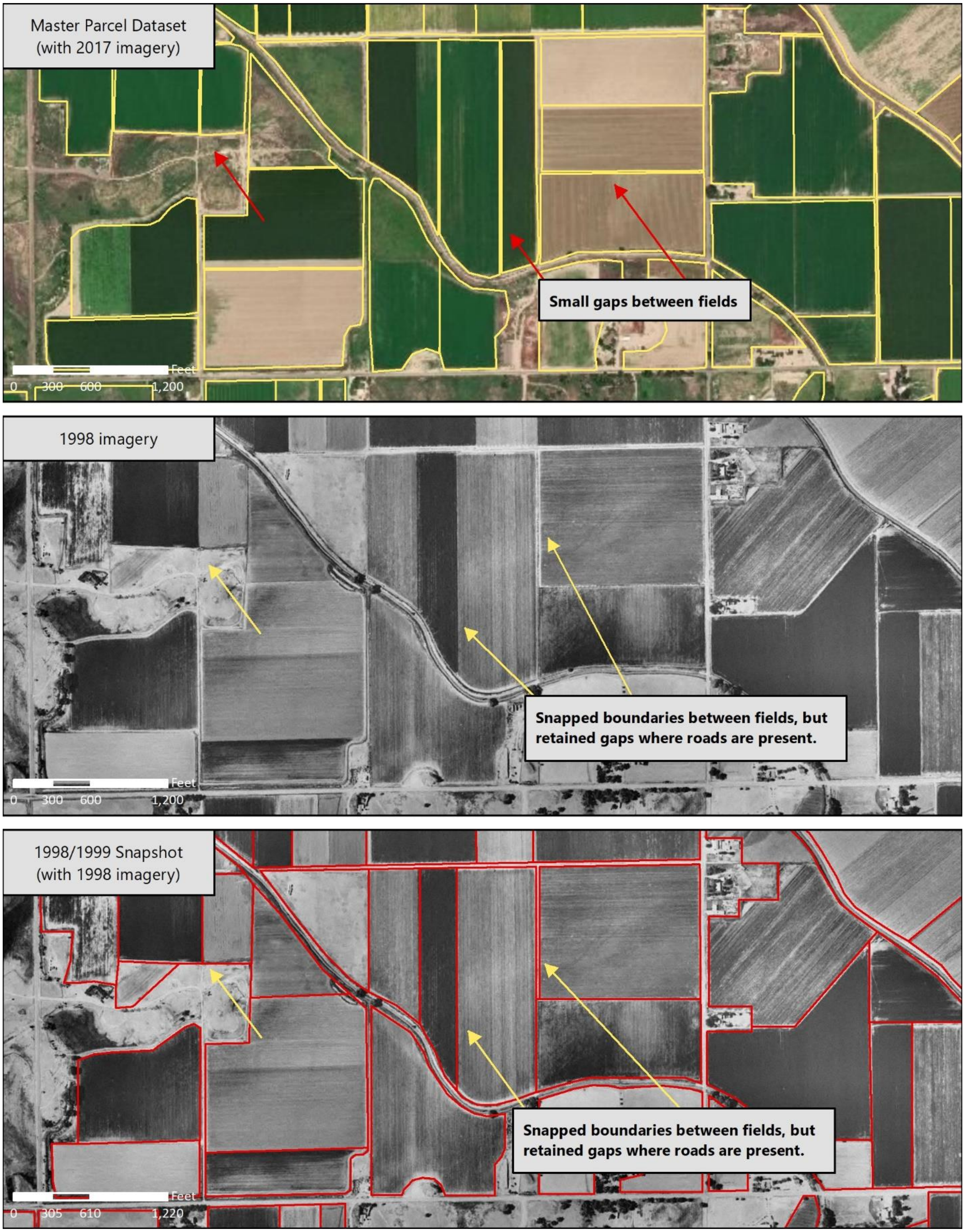


Figure 3 – This area is just southeast of Rocky Ford within the HIM area. It displays the process of snapping adjacent parcels where no road exists.

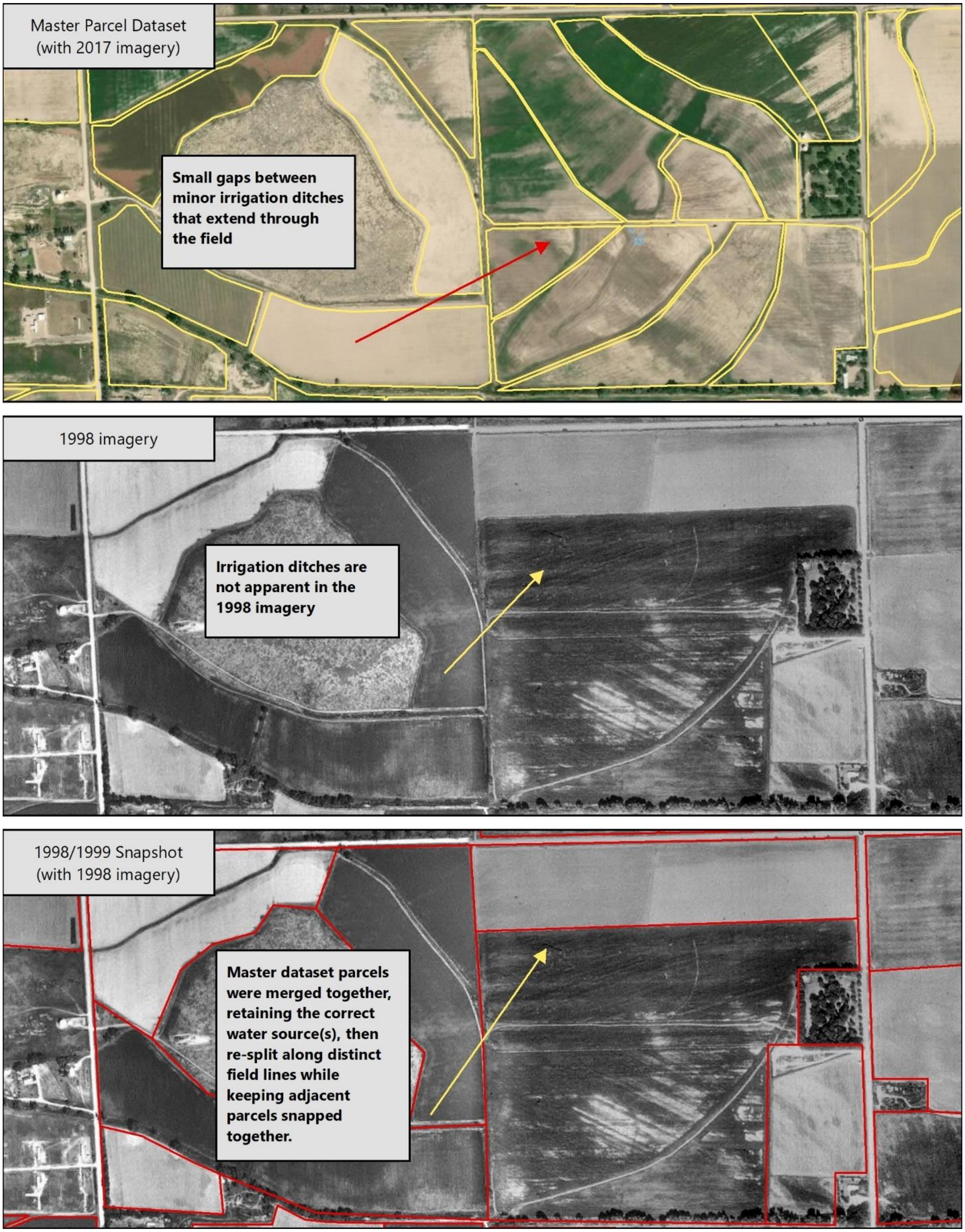


Figure 4 – This area is north and west of Lamar within the HIM area. It displays the process of removing gaps between minor laterals.

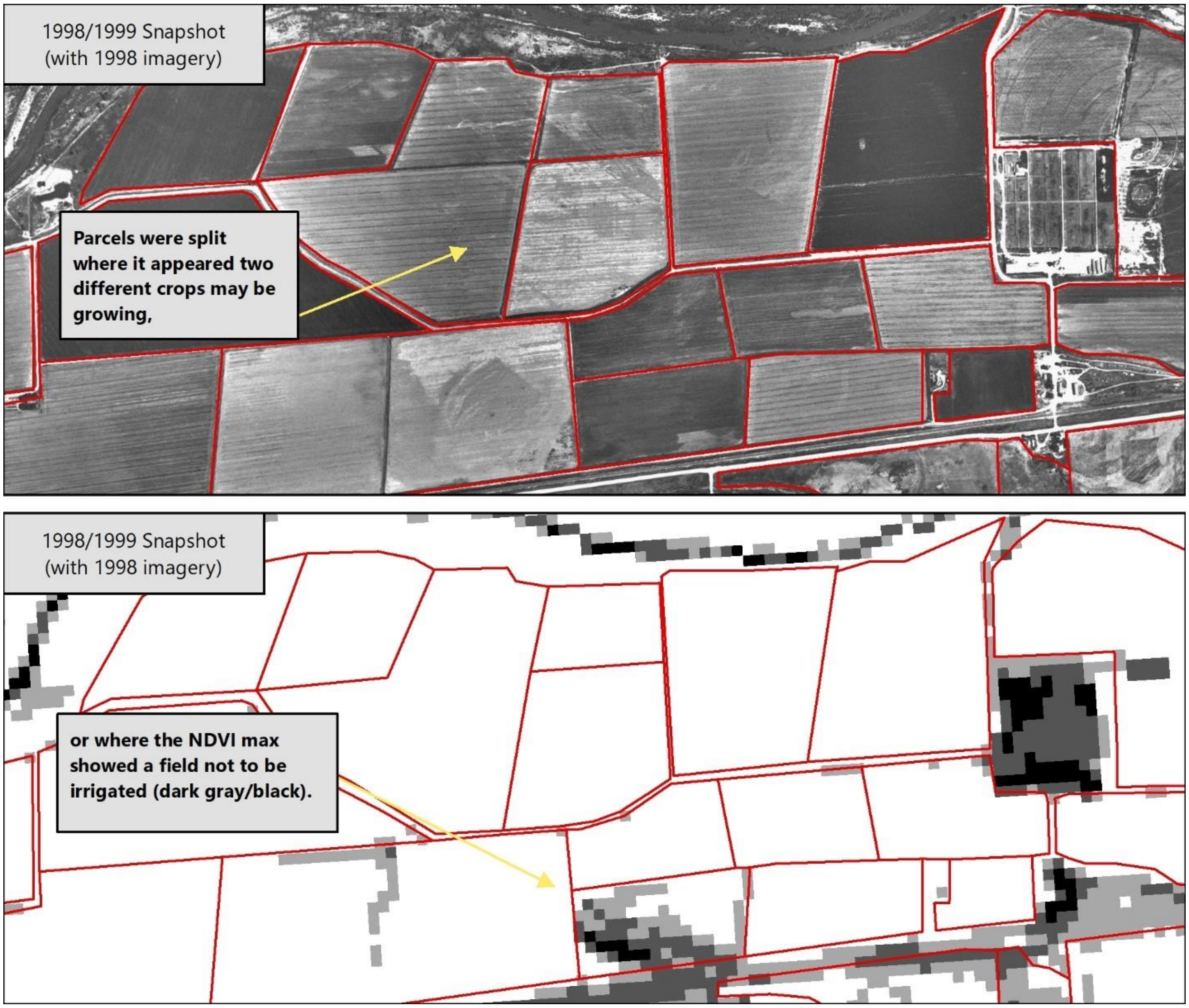


Figure 5 – This area is just south of the Arkansas River and east of John Martin Reservoir within the HIM area. The figure displays how parcels were split where it appeared two different crop types were growing and/or where the NDVImax dataset showed where land was not being irrigated.

Following the method of merging parcels together by water source, then re-cutting, splitting, or re-shaping as needed, resulted in a quicker and more seamless process to digitize the remaining earlier snapshot years. The resulting datasets are topologically correct in that the parcels are either snapped together (i.e. they share a boundary) or have consistently sized gaps between parcels where roads or large ditches exist. For example, Figure 6 shows an area just north and west of John Martin reservoir from 2010 (the master parcel dataset) through 1954 (excluding 1988). The figure typifies changes that the parcel extents underwent to account for changing crop type, road configurations, ditch extents, and/or homesteads.

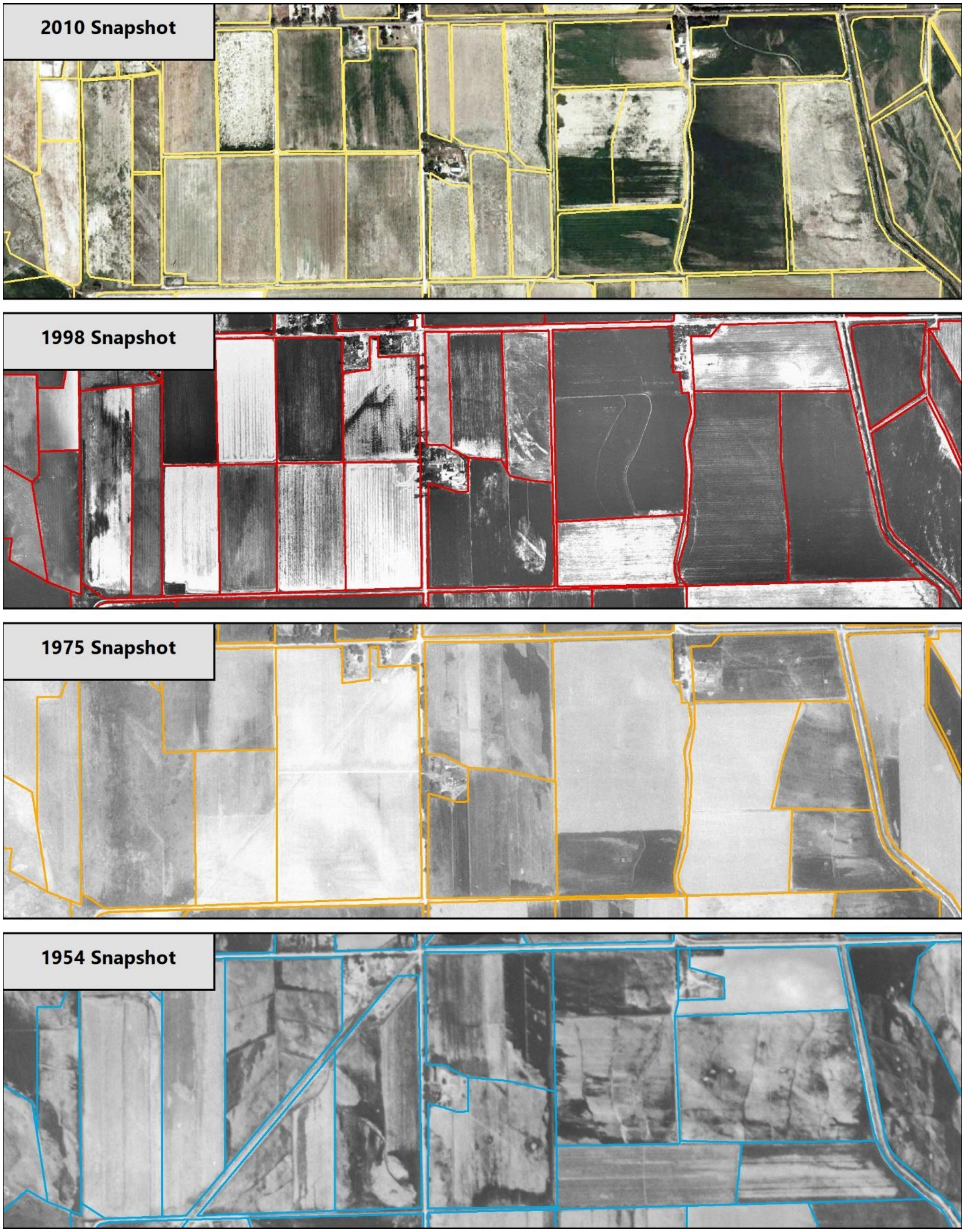


Figure 6 – This area is north and west of John Martin reservoir. The parcels have been re-shaped going back in time to match the extent of the fields and excludes where new homesteads and roads appear between snapshots.

2.2.2 Decision-Making for Area Outside the HIM

Irrigated parcels outside the HIM extent are often significantly different than those inside the HIM in shape, extent, and overall air photo appearance. Parcels outside the HIM tend to be more irregular in shape with less defined field boundaries than inside the HIM. Also, parcel size tends to be larger compared to parcels inside the HIM and parcels are often not adjacent to each other. Decision-making for defining parcel and field extents varied slightly from the process followed for areas within the HIM. The following list discusses these decisions and issues that were uniquely encountered outside the HIM.

- In the master parcel set, digitized pivot sprinkler fields appear as both a standalone circle and as a circle inscribed into a square creating “corner fields”. These corner fields were only digitized on standalone pivot fields if there was evidence of irrigation (e.g. Figure 7).The additional acreage in the corners of the square is often irrigated either by runoff from the sprinkler irrigation or by an end gun on the sprinkler itself. For the majority of the Arkansas River basin, these corner fields were considered to be irrigated by runoff and flood irrigation practices. However, in eastern districts 66 and 67, these corner fields were considered to be irrigated by the sprinkler.

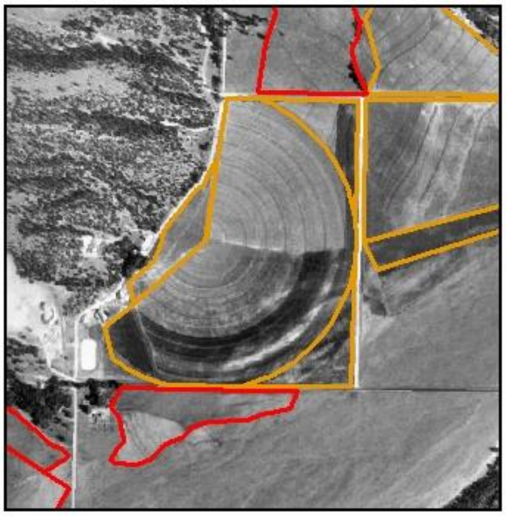


Figure 7 – Image of pivot with irrigated corners

- If not already digitized in the master parcel dataset, community and commercial irrigated lawns such as golf courses and baseball fields were not digitized.

- Districts at higher elevations (e.g. 11, 12, 13, etc.) had a significant number of parcels in the master parcel dataset marked with the crop type code ‘GRASS_PASTURE’. These particular parcels were also generally irregular in shape and did not follow a clearly defined field or landmark when compared to imagery (e.g. Figure 8). Some of these parcels appeared to coincide with a riparian vegetation zone along tributary streams. These fields were incorporated into the historic irrigated parcel datasets unaltered, and irrigated status was decided through the processes discussed in a later section. The only instance in which these fields were changed was when there was clear evidence seen in the imagery that the land was shown to be purposefully irrigated.

Figure 8 – Image of higher elevation irrigated fields with irregular shapes found in the master parcel dataset

- Tree farms and orchards existed in earlier snapshot years. The general rule for digitizing tree farms and orchards was based on signs of active care and irrigation (e.g. trees did not appear to be sparse, but rather vegetated and/or relatively densely spaced). Orchards were predominantly found in Water District 12, (Canon City), but were also found sparsely elsewhere. Though there are a few orchards still active today within the bounds of the 2010 dataset, they can be found with increasing prevalence going back in time as seen in an area within Canon City in Figure 9.

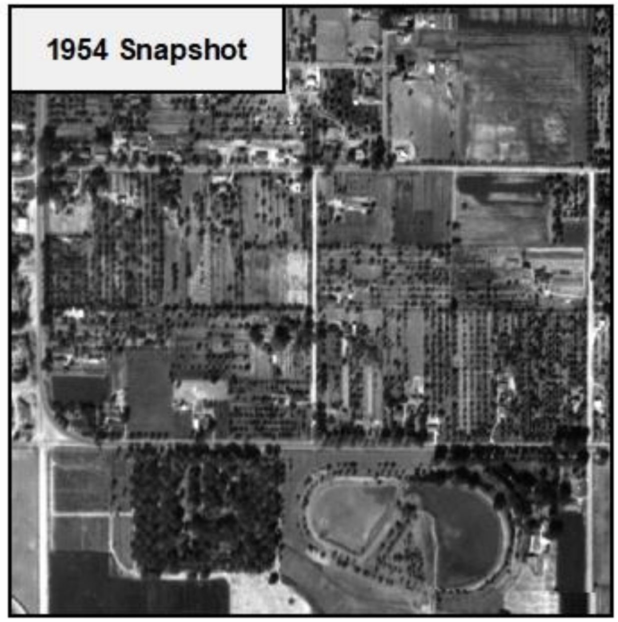


Figure 9 – Area within Canon City where orchards/tree farms were common

- As a rule, lawns and backyards were not digitized unless already included in the master parcel dataset. However, the master parcel dataset had some occurrences of lawns and backyards digitized in the Canon City area. These areas appear to be remnants of larger fields that have decreased in size due to housing development in the area over the years (e.g. Figure 10). It was also commonplace for homeowners in the area to settle on the land with their own small fields of crops and orchards or hobby farms. As such, additional context was used when deciding to digitize smaller fields in Canon City such as if the field (possibly a lawn) in question was part of much larger, clearly irrigated farm fields in earlier snapshots. If this was the case, then the field was digitized into the irrigated parcel dataset, subsequently expanding the acreage going back through time.

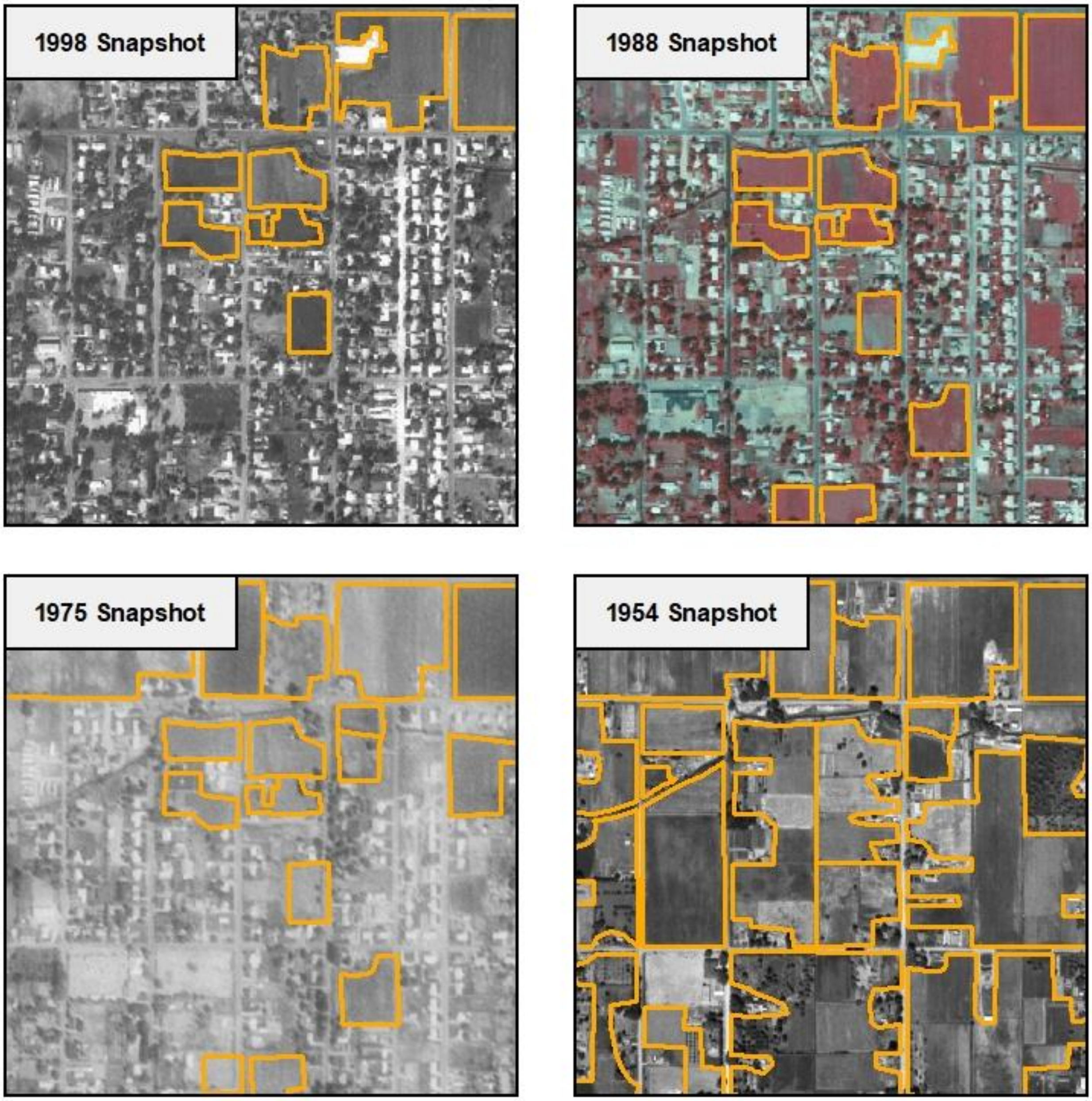


Figure 10 – Areas within Canon City where small fields (possibly lawns) in later snapshots were part of a larger field in earlier snapshots

2.3 Classify Each Parcel's Irrigation Status

2.3.1 Post-1985 Irrigated Status

The irrigated status for parcels within the post-1985 snapshots was evaluated with the NDVImax dataset. As stated previously, the NDVImax *is representative of the maximum amount of healthy vegetative biomass observed through the growing season at that location.* The "greenness" of the vegetation can be equated to whether or not a parcel was irrigated if a threshold value is applied to the NDVImax dataset. For this task, at the recommendation of CDWR, a NDVI threshold value of 150 was set as the delineator between irrigated and non-irrigated parcels. The NDVImax dataset was evaluated through zonal statistics collected for each parcel within each snapshot dataset. Zonal statistics is a tool in ArcGIS' spatial analyst extension that calculates a specified statistic of a raster dataset within a "zone". In this case, zones were represented by individual parcels and the statistic extracted was the ***mean*** NDVI value. Figure 11 shows an example output of zonal statistics where the mean NDVI value is denoted in red inside the parcel, or zone.

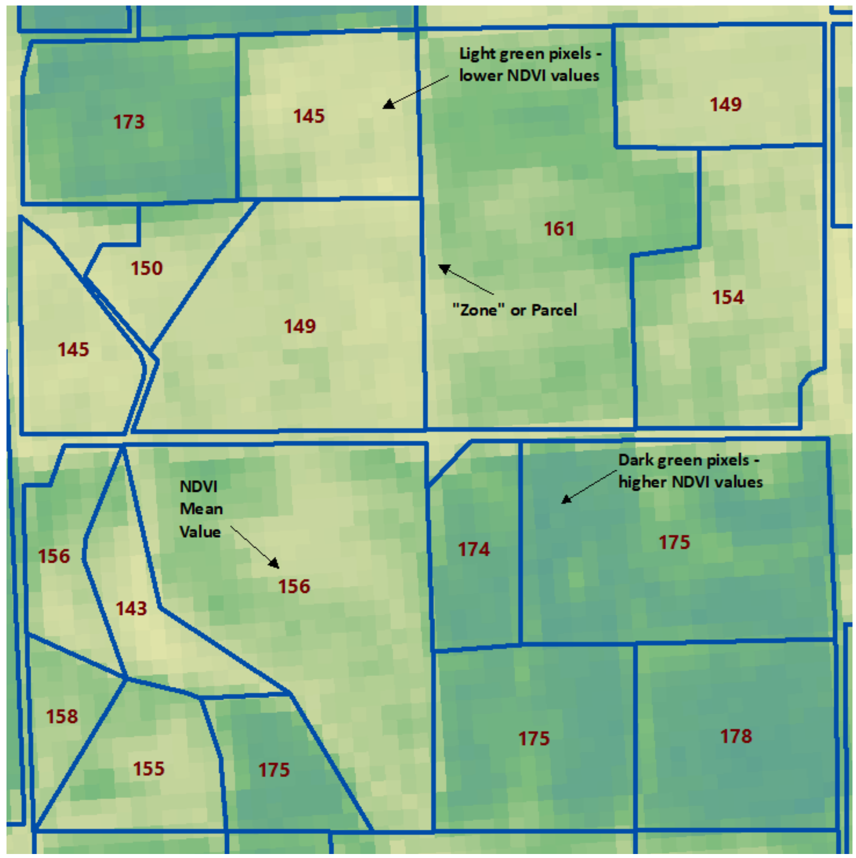


Figure 11 – Example of zonal statistics output using the NDVImax raster dataset

Before zonal statistics was performed, the parcel datasets were buffered internally by 30 meters. Buffering the parcels this way reduced the edge effects that the 30-meter NDVImax dataset may have had on the parcel boundaries. After zonal statistics was run on the internally buffered parcels the resultant statistics table was joined to the irrigated parcel datasets using a unique numeric identifier. Then, a query was run on the parcels to select and assign a "YES" to each parcel that had an NDVImax mean value greater than or equal to 150. The mean NDVImax values were retained in the final parcel datasets' attribute tables for potential adjustments to the threshold that may be needed for future use.

2.3.2 Pre-1985 Irrigated Status

Because satellite imagery is not available before 1985, the NDVImax dataset is not available for the 1975 and 1954 snapshot years. Determining irrigated status for a parcel from just an air photo can be challenging depending on the air photo date, growth pattern of the crop irrigated, natural precipitation, and ground water table conditions. The irrigated status for parcels in the 1975 and 1954 snapshots was evaluated in a 3-step method. It is important to note that the irrigation status decision for the 1975 and 1954 snapshots were not based solely on the conditions shown in the snapshot photo, but rather considered supporting data over a 15-year span, where the 1975 snapshot is based on data from the years 1965-1979 and the 1954 snapshot is based on data from the years 1950-1964. This means that even if a field may not appear to be actively irrigated in the corresponding snapshot year's aerial imagery, as long as there was evidence that indicated that the field may have been irrigated at some point close in time to the aerial image date, it was designated as irrigated. This was the first and most important step in the 3-step method. Air photo evidence indicating that a field was potentially irrigated includes darker, presumably wet, areas within the field boundary, fields that appear to have been harvested (homogenous coloring), and absence of native vegetation within field boundary.

The second step, which was only used if the irrigated status of the field was difficult to discern in the snapshot year imagery, was to review later snapshots (1988 and 1998) and compare the irrigation status that was assigned through the NDVImax threshold to how the field looked in the aerial imagery. While it is reasonable to consider future irrigation status to derive past irrigation status, this method illustrated the difficulty in assigning irrigation status based on air photos alone; in some cases, there were instances when a field would appear to be irrigated in the pre-1985 snapshots, but the more recent NDVImax mean value in that field may have been below the threshold for irrigated status. Figure 12 shows an example of two parcels during the 1998 and 1988 snapshots that both could appear as irrigated in the imagery, but have varying irrigated status as calculated by the NDVImax.

The third step used to determine irrigated status was to do a general assessment of historic ditch diversions. HRS compiled the ditch diversion records exported from Hydrobase by the SEO for the two 15-year periods represented by the 1975 and 1954 snapshots as well as for 1998 and 1988 snapshots for major ditches within Division 2. With the compiled records, diversion ratios were created for each active ditch comparing the reported amount of diverted water (acre-feet) to the amount of irrigated land served by that diversion (acreage). At lower elevations, it was common to see ratios of 2:1 (meaning 2 acre-feet of irrigation water were diverted per acre irrigated) or 3:1. At higher elevations ratios of 10:1 or higher were common. These ratios were compared between each snapshot for each active ditch to identify if there was a significant increase or decrease between years. A significant difference in ratio between years was assumed to indicate that a ditch had too much or too little irrigated acreage assigned to it, whether that be from a wrong surface water WDID assignment or too many parcels designated as irrigated or not irrigated. Manual adjustments to parcels' irrigated status in the 1975 and 1954 snapshots were made, as necessary, to better align with the 1998 and 1988 diversion ratios.

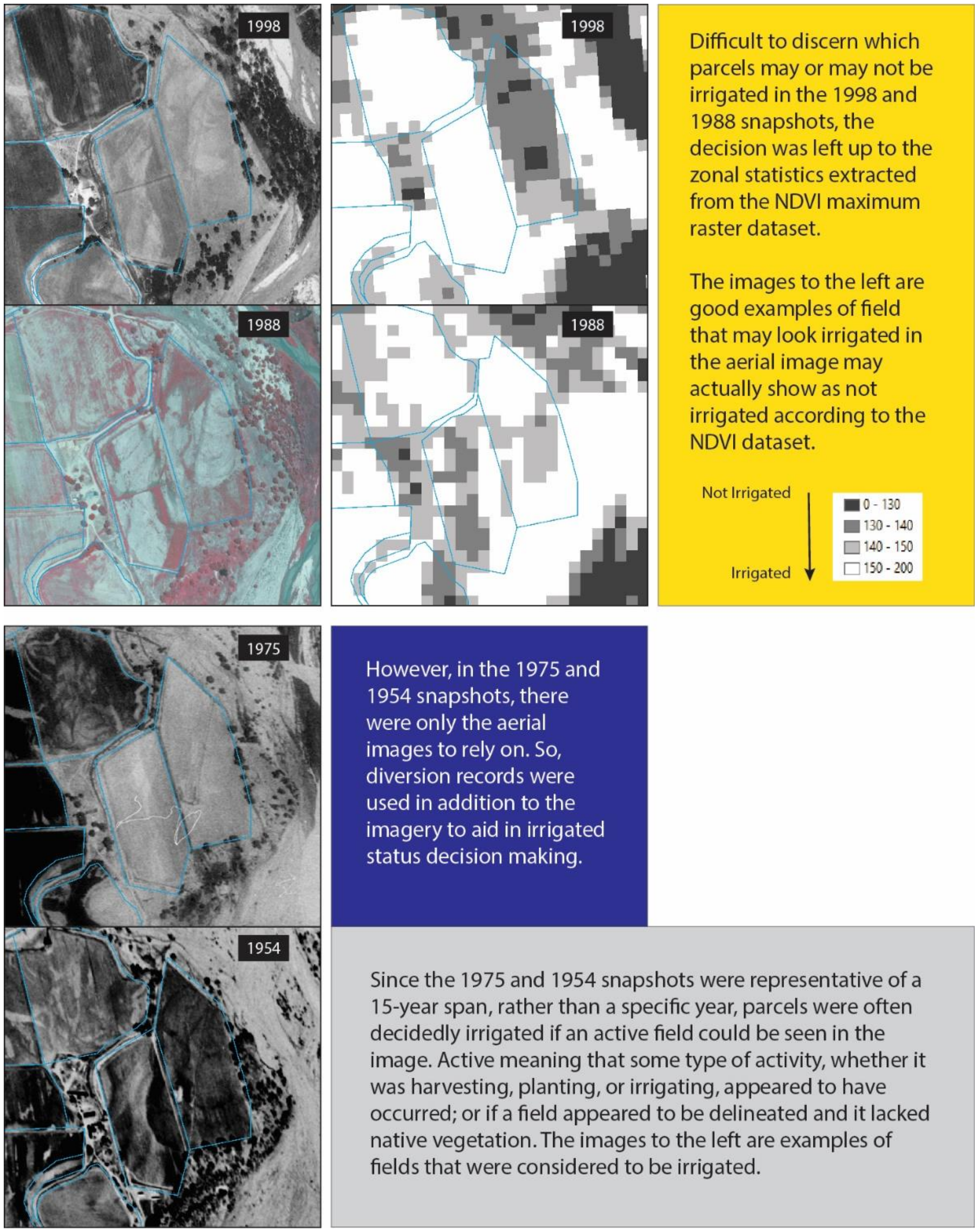


Figure 12 – Example of two parcels and how they appear in the snapshot aerial images. Parcels may appear to be irrigated in the aerial imager, but in fact may be non-irrigated as determined by the NDVImax mean value

3.0 IRRIGATED PARCEL ATTRIBUTE TABLE ADJUSTMENTS

3.1 Decreed Dry-Up Areas

Between the 1954 and 1998 snapshots, areas within the Arkansas River basin went through a loss of irrigated acreage due to water sales, commonly known as "dry-up areas". These dry-up areas are listed in a document maintained by Division 2 entitled, "Historical Losses of Irrigated Acreage through Water Sales" (Historical Loss Document). HRS reviewed the Historical Loss Document and those areas where dry-up acreage was reported[6] and occurred sometime between the snapshot years (1954-1998), as the document spanned the years between 1955 and 2007, are shown in Figure 13 below.

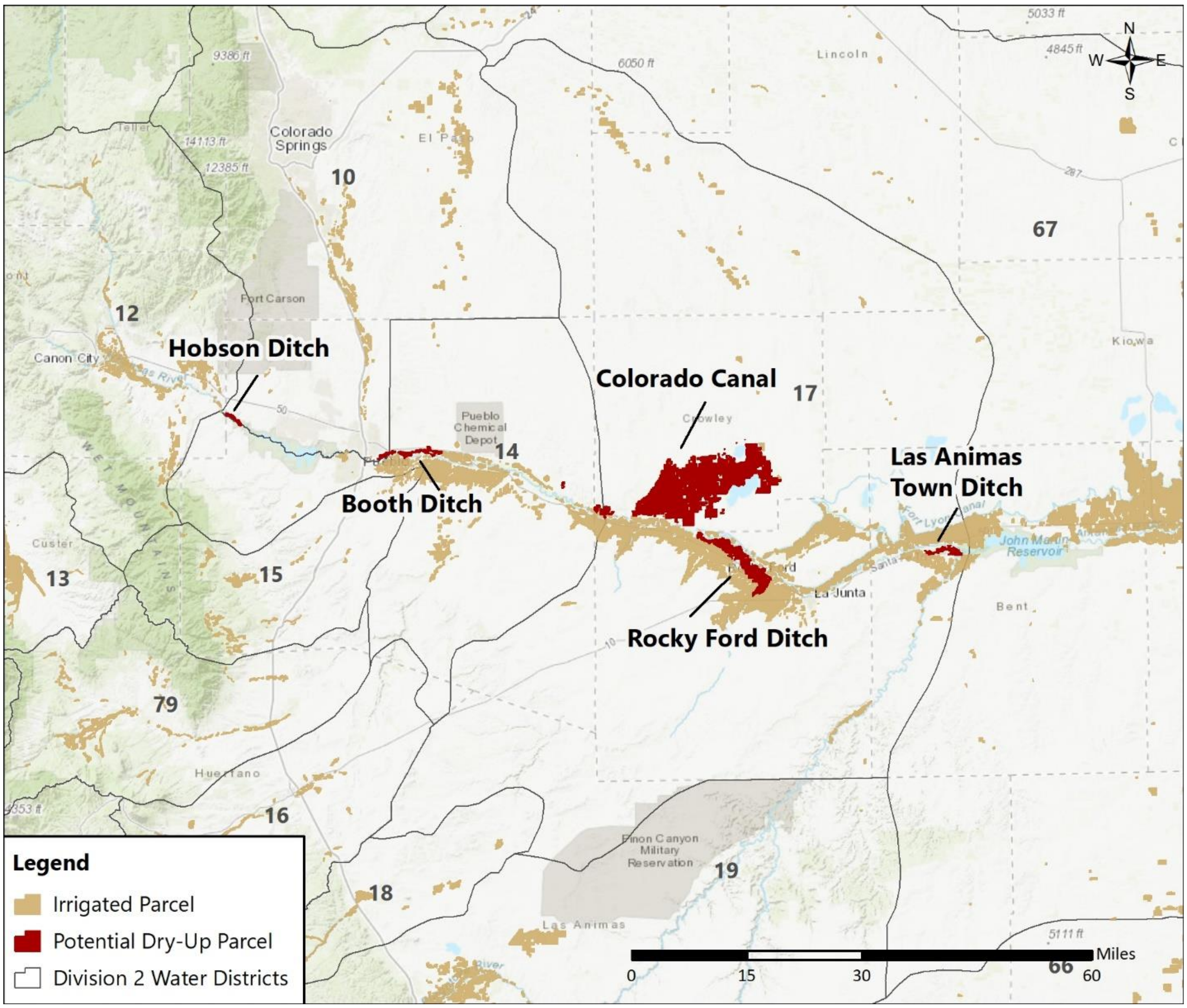


Figure 13 – Dry-Up Areas Investigated for historic snapshots.

[6] Some dry-up acreage amounts could not be confirmed in the Historical Loss Document, thus were not included in the assessment nor in this discussion. These water sales include: Otero Ditch (1955), Highline Canal (1971), Las Animas Consolidated Extension (1984), and Highline (1986)

The five areas shown in Figure 13 were reviewed in each irrigated parcel dataset and those parcels that may have been affected by water sales were noted in the dataset attribute table. The notes were inserted in the datasets into two newly added attribute fields named, 'POSS_DryUp' and 'DryUpComment'. The 'POSS_DryUp' field was designated as "YES" if that particular parcel may have been affected by water sales and left as <Null> if not. If the 'POSS_DryUp' field was designated as "YES", then the 'DryUpComment' field was populated with the ditch name that was part of the water sales in that area and other information such as if the parcel has an associated well attached to it. The irrigated status (field name 'IRRIG_##') was left "as-is", meaning that if the NDVImax method of determining irrigated status resulted in a "YES", then it remained a "YES". This convention was also used for the pre-1985 irrigated parcel datasets. The reason for keeping the irrigated status as a "YES" in the attribute table even if that particular parcel may have been located within an area influenced by water sales was because there could potentially be other factors contributing to the irrigated status of a parcel, such as a well or a drain. The following sections and figures present those areas listed in the Historical Loss Document that have confirmed dry-up acreage and displays those parcels that were denoted as "YES" in the 'POSS_DryUp' field in the attribute table.

3.1.1 Las Animas Town Ditch to Highline Canal – 1971

Irrigated acreage adjacent to the Town of Las Animas was digitized according to what was apparently irrigated in the 1954 aerial imagery (green parcels in the figure below). Any of these newly digitized 1954 parcels that were also digitized in the any of the later snapshots were denoted as possibly being affected by water sales that occurred during 1971. Some of these areas are still currently being irrigated due to the parcels having a groundwater right attached to them.

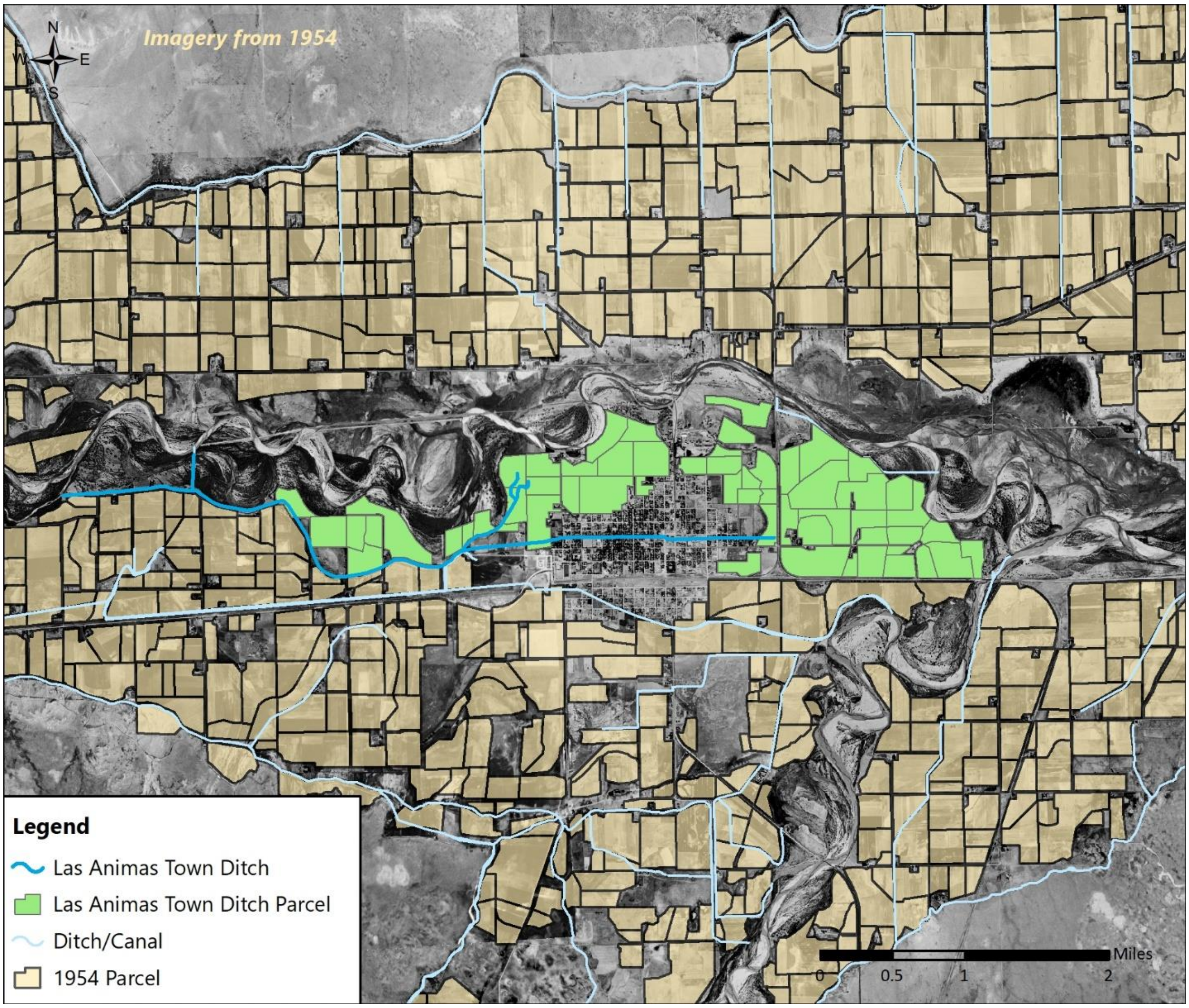


Figure 14 – Parcels adjacent to and possibly irrigated by Las Animas Town Ditch

3.1.2 Booth Orchard to City of Pueblo – 1972

Irrigated acreage within Booth Orchard was digitized according to what was apparently irrigated in the 1954 aerial imagery (orange parcels in the figure below). Any of these newly digitized 1954 areas that were also digitized in the any of the later snapshots were denoted as possibly being affected by water sales in the attribute table. Some of these areas may still be irrigated due to the parcels having a groundwater right attached to it.

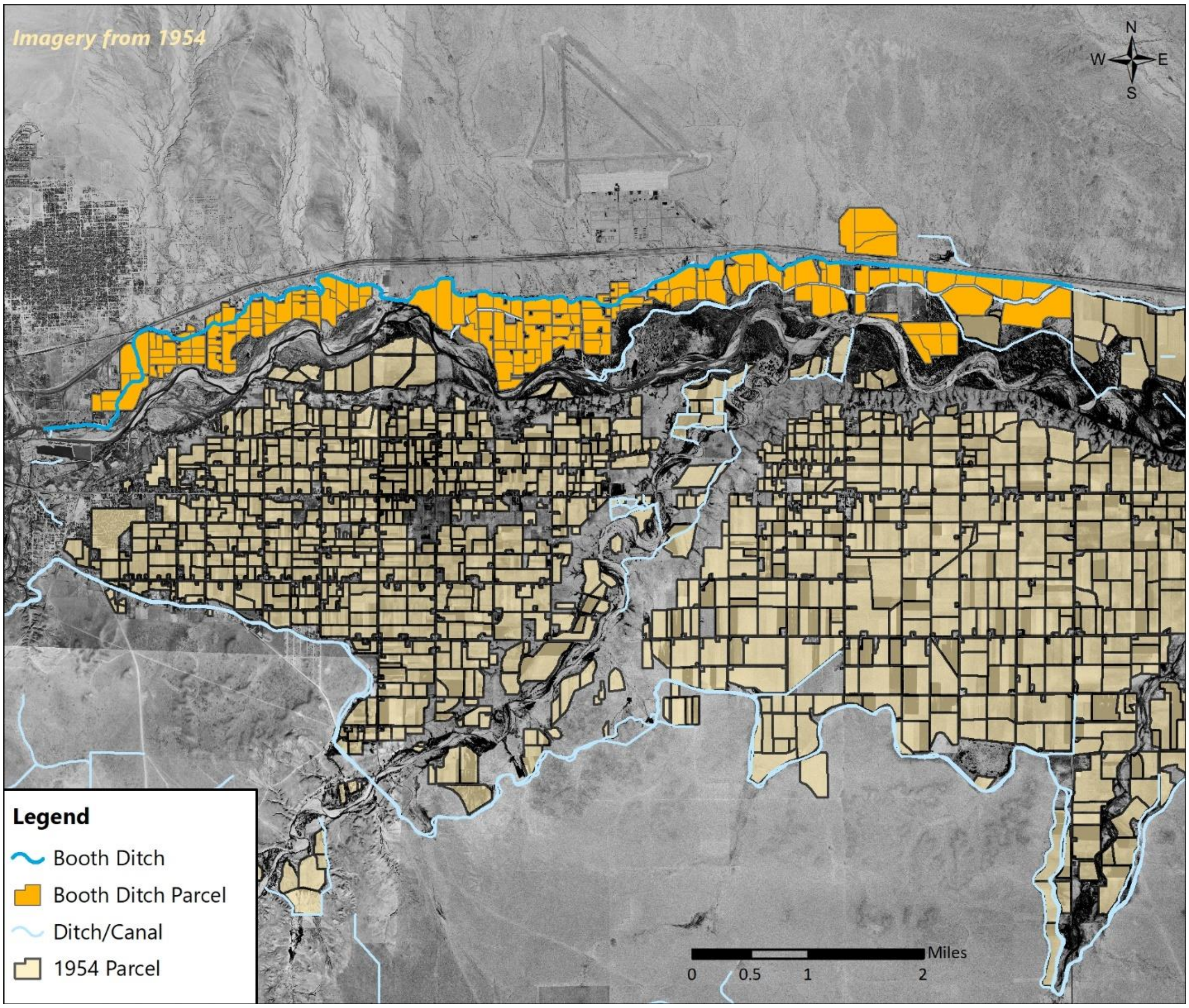


Figure 15 – Parcel adjacent to and irrigated by Booth Ditch

3.1.3 Hobson Ditch to City of Pueblo – 1973

Irrigated acreage adjacent to the historic location of Hobson Ditch was digitized according to what was apparently irrigated in the 1954 aerial imagery (yellow parcels in the figure below). None of these areas appeared to be irrigated after the 1954 snapshot; therefore, these parcels were not digitized in later snapshots.

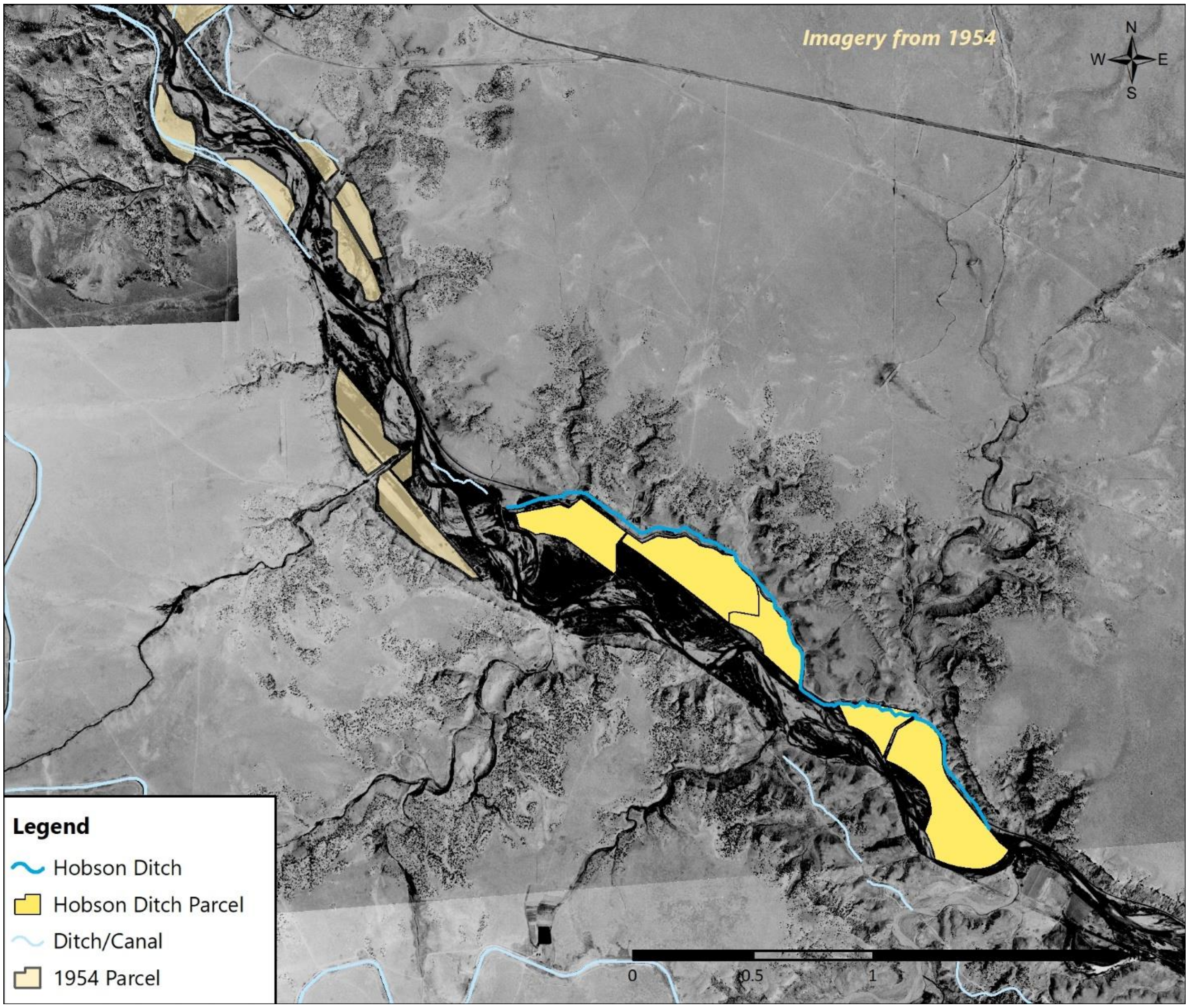


Figure 16 – Parcels irrigated by Hobson Ditch

3.1.4 Colorado Canal - 1985

The Division 2 GIS staff provided a shapefile of parcels included in the Colorado canal dry-up area (purple parcels in figure below). The corresponding parcels in the 1988 and 1998 irrigated parcel datasets were denoted as possibly being affected by water sales; however, many of these parcels were designated as being irrigated by the NDVImax method. The reason for this may be due to having a groundwater right attached to them.

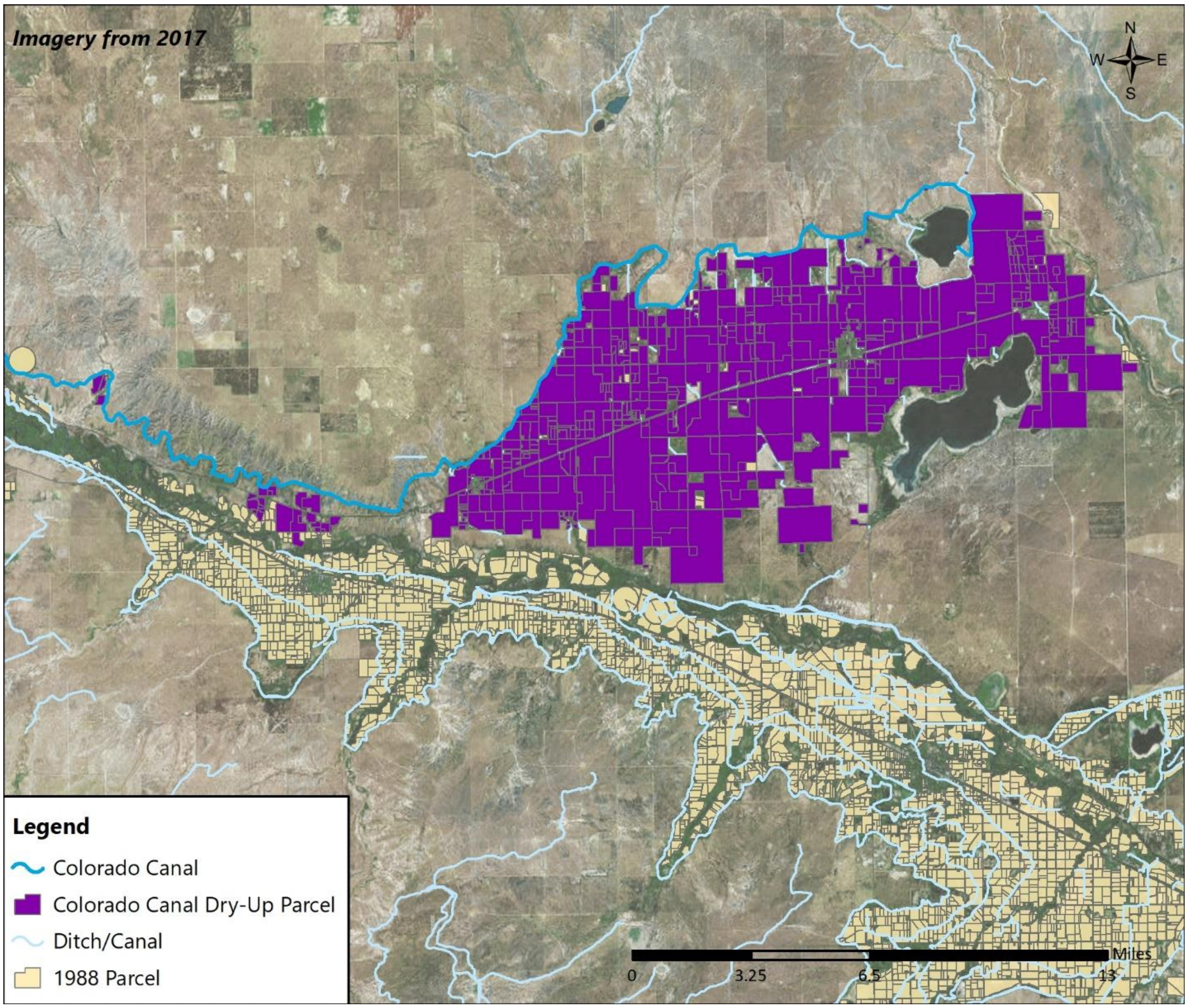


Figure 17 – Parcels irrigated by Colorado Canal

3.1.5 Rocky Ford to Aurora

Irrigated acreage adjacent to the Rocky Ford ditch was digitized according to what was apparently irrigated in the 1954 and 1975 aerial imagery (green parcels in the figure below). These digitized areas that were also digitized in any of the later snapshots were denoted as possibly being affected by water sales. Some of these areas may still be irrigated due to the parcels having a groundwater right attached to them.

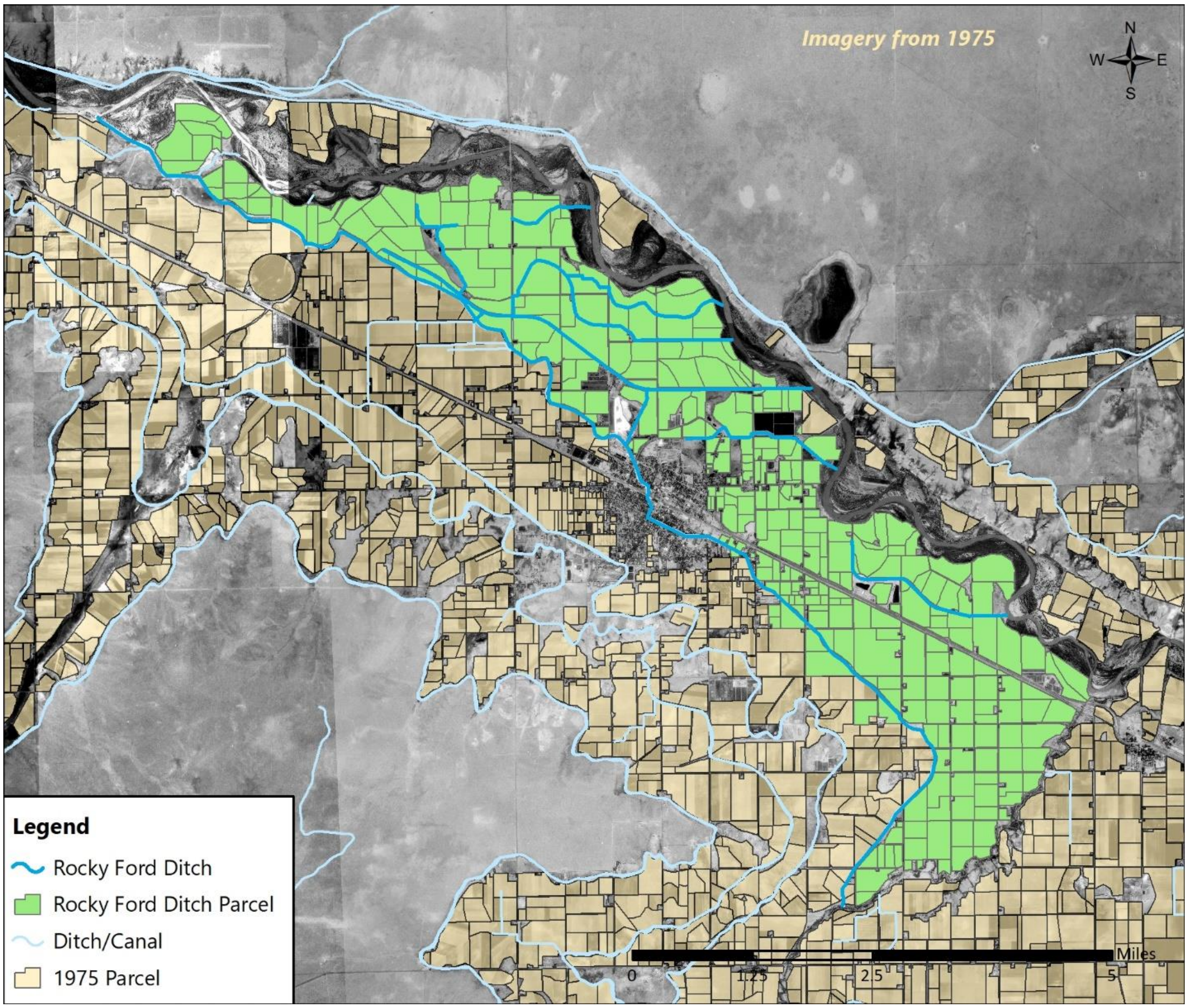


Figure 18 – Parcel irrigated by Rock Ford Ditch

3.2 Remove Groundwater Source from Snapshot Year, as Necessary

HRS worked backwards in time from the 2010 irrigated parcel dataset to generate irrigated parcel dataset for snapshots 1954, 1975, 1988, and 1998. One result of this process is that all wells (designated with a GWDID in the parcel dataset attribute tables) included in the 2010 irrigated parcel dataset remained in each subsequent snapshot. Thus, once all snapshots were digitized, wells that were not yet drilled at the time of the snapshot year needed to be removed from the corresponding irrigated parcel dataset. For example, wells drilled after 1998 were removed from the 1998 snapshot. It is important to note that a parcel may have had up to 20 wells (GWDIDs) associated with it, so all GWID attributes were assessed for each parcel. Also, unlike the 3-step method used to assign the surface water-related irrigated status of the parcels, the ground water source(s) assigned to each parcel in the 1975 and 1954 snapshots were representative of only that year instead of a 15-year span. This is true only for this task as well as the following task (adding historic groundwater sources). The total number of GWDIDs that were removed from each snapshot varied between 100 and 1,200, with the fewest removed from the 1998 snapshot and the most removed from the 1954 snapshot.

3.3 Add Historic Groundwater Sources to Snapshot Years, as Necessary

Historic wells are defined as wells that were in operation sometime between 1954 and 1999, but were no longer in service in 2010. Historic wells were not included in the master parcel dataset and needed to be added into the relevant historic snapshots by assigning each historic well to a specific parcel. Datasets of historic wells were provided in two separate shapefiles, one by the SEO and one by Division 2. Each dataset contained between 400 and 500 wells. The historic wells were assigned to parcels in the historic snapshots with the ET Geo Wizards™ tool, Global Snap Points. This tool is a plug-in for ArcMap that snaps points to polygons within a specified distance and was used to automatically snap wells to the nearest parcel within a quarter mile linear distance. If there was no parcel within a quarter mile distance then the well point was not automatically snapped and, instead, the area was visually assessed by HRS using aerial imagery and the NDVImax dataset. If there was a visibly irrigated, but not digitized field within a quarter mile of the historic well, then that field was digitized and the well's GWDID was manually attributed to the parcel. If there was no visibly irrigated area within a quarter mile, the historic well was not attributed to any parcel (Table 1).

> It is important to note that the method of automatically snapping wells to the closest parcel within a specified distance did not account for natural or manmade boundaries such as rivers or roads. So, it may be possible that some wells were snapped to a parcel that may be across a boundary from the well location. This is a limitation of assigning wells with an automatic process.

SEO Dataset				
Year	1954	1975	1988	1998
Automatically Attributed	67%	65%	64%	72%
Manually Attributed	23%	21%	26%	23%
Total Attributed	90%	86%	90%	95%
Division 2 Dataset				
Year	1954	1975	1988	1998
Automatically Attributed	95%	95%	94%	92%
Manually Attributed	4%	2%	3%	4%
Total Attributed	>99%	97%	97%	96%
Combined SEO and Division 2 Datasets				
Automatically Attributed	79%	80%	79%	76%
Manually Attributed	14%	12%	14%	20%
Total Attributed	**93%**	**92%**	**93%**	**96%**

Table 1 – Percentages of wells automatically and manually attribute to parcels

For all snapshot years, at least 90% of historic wells were attributed to a parcel either automatically or manually. A larger percentage of wells in the Division 2 dataset were automatically attributed as all of these wells were located within the HIM Area and thus more of them were within a quarter mile of an already digitized parcel. The SEO dataset contained mostly wells outside the HIM Area and thus, more wells were manually attributed to new parcels. The wells that were not attributed to a parcel because they were not within a quarter mile of an irrigated parcel are noted in the attribute table for the historic wells shapefile. The historic wells shapefile is part of the digital data deliverable.

4.0 QUALITY CONTROL CHECKS

Quality control (QC) of datasets this large is important both during and after the data processing work. The continuous and rigorous QC steps employed during this project greatly reduced the risk of errors propagating through working versions of the deliverables and resulted in a high-quality deliverable GIS dataset. The QC checks included: topology check, general quality checks, and irrigation type check. The following subsections describe how each quality check was accomplished.

4.1 Topology Check

Topology, or the spatial relationships between adjacent or neighboring polygons, was checked for each snapshot using the tool, *Clean Polygons.* Clean Polygons tool is an ET Geo Wizards tool, a plug-in tool for ArcMap, which checks topological correctness of a polygon feature dataset. When run, the tool exports a point shapefile that identifies where overlapping polygons exist (an obvious error when the polygons delineate parcels). The tolerance for each snapshot was set to 0.05 meter to ensure that even small overlaps, possibly due to unsnapped vertices, between polygons were cleaned up and snapped. This tool was especially important within the HIM area where most polygons are snapped to an adjacent polygon. Using the exported point shapefile as a guide, the polygons were revised, where necessary, by either snapping vertices to neighboring vertices, redrawing polygon extents, or adding vertices to polygon edges. The Clean Polygons tool was run on the irrigated parcel datasets frequently during the digitization process to ensure topological correctness was retained throughout the process.

4.2 General Quality Checks

A group a quality checks, referred to herein as “general quality checks”, was performed concurrently as the historic irrigated parcel datasets were being developed. These general quality checks focused on the completeness of each snapshot and associated data and involved:

- Boundary check – Because the 2010 master parcels were extracted and re-saved to multiple GIS coverages based on water district , an overall visual check at the water district boundaries was completed to ensure that no parcel geographically located at a water district boundary was missed or duplicated.
- General clean-up of the attribute table – The irrigated parcel attribute table was cleaned up by visual inspection and manual adjustments through data queries to: (1) remove internal notes that may have been left behind during the digitization process; (2) ensure that any field that should be populated contains the pertinent data; and (3) ensure that no field was duplicated. This process was carried out multiple times during the course of Subtask 1.3 because more fields were added during the crop-typing process (described in a later section).
- NDVI spot checks – Visual spot checks were made to ensure that the NDVImax method for assigning irrigated status was executed correctly in all water districts
- Irrigation type checks – Visual spot checks were made to ensure that the irrigation type (i.e. sprinkler versus flood versus drip) was properly assigned to the parcels. Spot checks were completed on approximately half of the parcels in each dataset by clicking through the attribute

table and comparing each checked parcel to the assigned irrigation type. Because there were no other data available to determine irrigation type, HRS followed these rules:

- Sprinkler – Parcel is circular, either a full circle or partial, in shape
- Flood – Parcel is rectangular or irregular in shape
- Drip – Aerial imagery shows clearly that the parcel is occupied by an orchard

Any parcel digitized or identified as an orchard or tree farm had the irrigation type designated as "Drip".

5.0 CROP TYPE ASSIGNMENT

5.1 Crop-Type Irrigated Parcels (post-1985)

Assigning crop types to irrigated parcels, or crop typing, for the 1988 and 1998 irrigated parcel datasets was established using satellite imagery, time-series NDVI reference curves, the maximum likelihood classifier (MLC) tool, and county crop statistics obtained from the United State Department of Agriculture (USDA). Initially, Farm Service Agency (FSA) crop type records were expected to be helpful with the crop typing effort. However, multiple attempts at acquiring the FSA records in a reasonably quick time frame were not successful due to the stringent FSA rules on releasing large amounts of this data. The effort dedicated to gathering the FSA records was abandoned and an alternate remote-sensing based method was developed.

The selected method included creating an NDVI "reference curve library" extracted from known crop types in the 2010 master parcel dataset and applying those reference curves to the 1988 and 1998 irrigated parcel datasets with the MLC tool in ArcMap. The crop typing method is similar to the method used in the State's South Platte Decision Support System (SPDSS). The method uses the pattern of NDVI values (crop "greenness") over a growing season to classify a crop based on a typical pattern observed for each crop. Some crops have very distinctive patterns, while others are similar to one another and require more detailed steps to improve the accuracy of crop classification.

Before applying the reference curve library method, however, the first task was to investigate whether the NDVI reference curves generated from 2010 data could be used to accurately crop type another year's irrigated parcels with known crop type. That is, the crop curves generated from a parcel coverage with a known crop type were used to test classify the crop type of another coverage with a known crop type and the percentage of successful crop type identifications examined. This type of investigation is discussed in the paper by Masialeti et al (2010), where the authors investigated the potential of using a time-series NDVI reference curve library for crops grown in 2005 to map crops in 2001 within the state of Kansas. Some of the methods discussed in the paper were taken into consideration during the HRS investigation, which consisted of:

- collecting NDVI curve data for major HIM crops (corn grain, sorghum grain, grass pasture, alfalfa, spring grain, fall wheat, and dry beans) from two different years' irrigated parcel datasets with known crop types (2010 and 2015);
- visually comparing the general phenological pattern of each crop type between each year; and
- numerically comparing the patterns between the two years with the Jeffries-Matusita (JM) statistic.

Based on the review of data collected during the investigation, HRS determined that NDVI curves created from 2010 crop data could be applied to the 1988 and 1998 irrigated parcel datasets with reasonable accuracy and that the accuracy could be improved by adding additional user-defined rules to some geographic areas. Figure 19 shows a basic outline of steps followed during the investigation and crop typing process and the following sections detail these steps and methods.

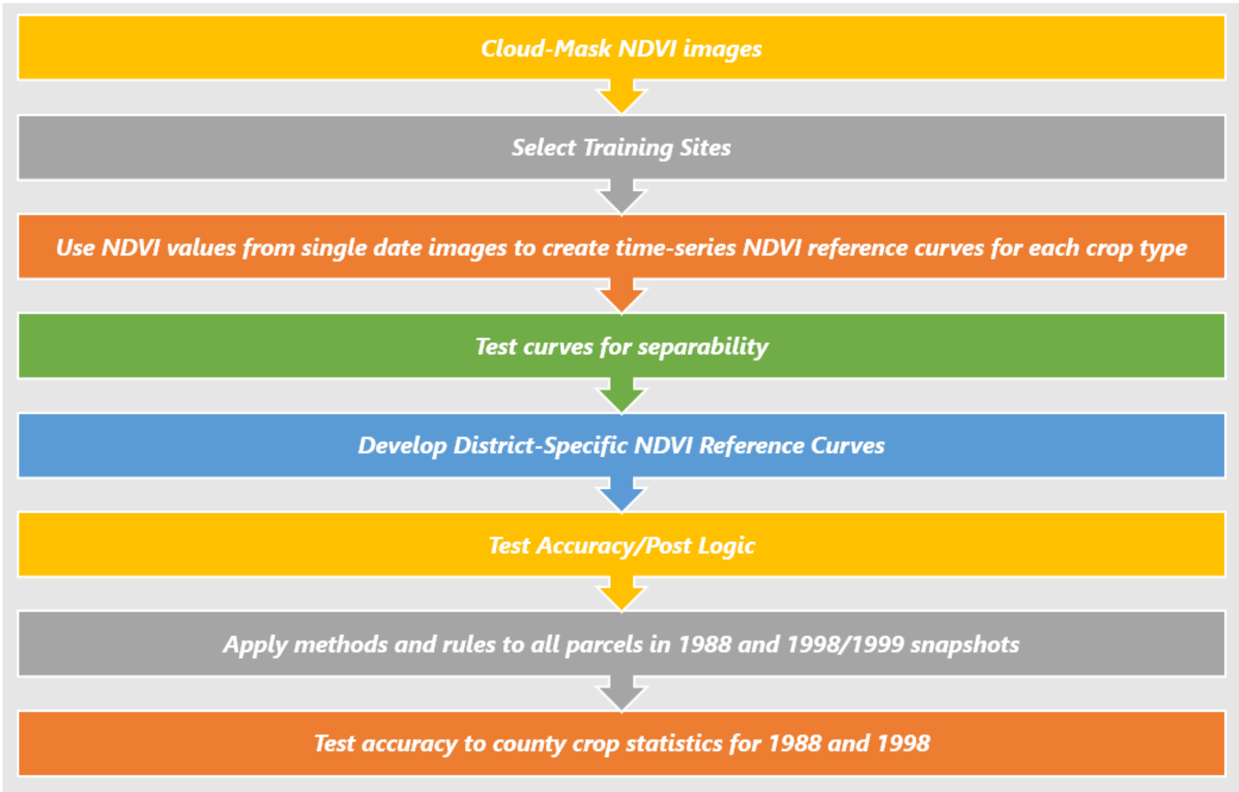


Figure 19 – Basic Crop-Typing Workflow

5.1.1 Cloud-Mask NDVI Images

The SEO provided processed single-date NDVI images from the 2010 and 2015 growing seasons. The general NDVI processing method is discussed in an earlier section entitled "Digitize/Adjust Potentially Irrigated Parcel Boundaries". HRS grouped the images into zones based on the Landsat 5 path and row location and these groups were termed EastCentral, WestCentral, and Southeast (Figure 20). A table of zones and corresponding dates of collection are included in Table 2 below. Before the NDVI images could be evaluated, they required clouds to be masked out of each, where needed. The cloud-masking process was important for the NDVI reference curve development process because clouds could potentially skew the set of values that make up the reference curves. Cloud-masking the images included a tedious visual review of each NDVI image and associated natural color satellite image, digitization of the clouds within ArcMap, and finally raster calculations to set the clouded areas to 'NULL' values. With the cloud pixels in each NDVI image set to NULL subsequent calculations within ArcGIS would ignore those areas.

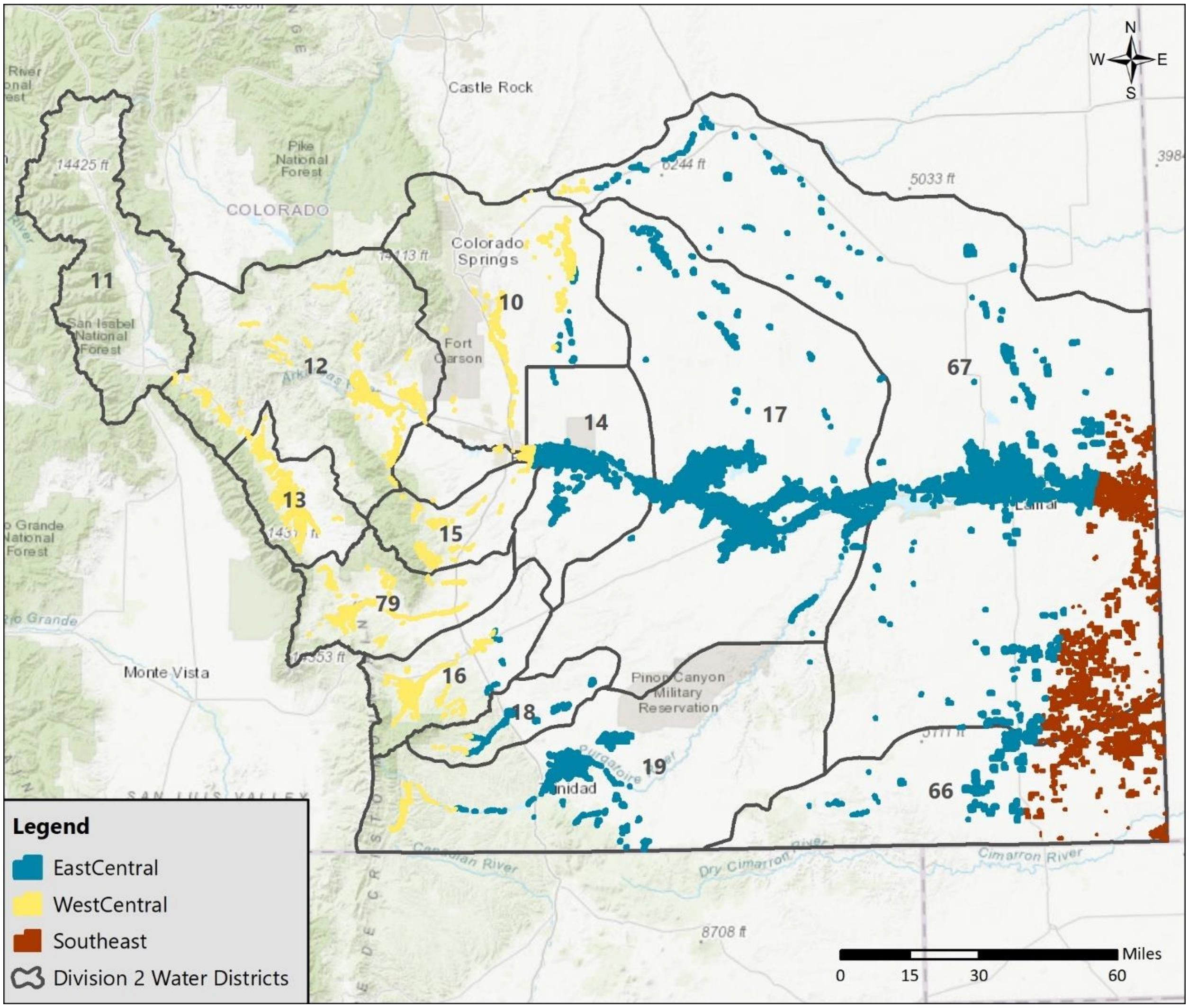


Figure 20 – Geographic location of the "zones", or LANDSAT swath extents.

Satellite Image Dates for 2010

DATE	WESTCENTRAL	EASTCENTRAL	SOUTHEAST
04/04		X	
04/27	X		
04/29			X
05/06		X	
05/22		X	
05/29	X		
05/31			X
06/16			X
06/23		X	
06/30	X		
07/02			X
07/09		X	
07/16	X		
07/18			X
08/01	X		
08/03			X
08/10		X	
08/17	X		
08/26		X	
09/02	X		
09/04			X
09/11		X	
09/18	X		
09/20			X
09/27		X	
10/04	X		
10/06			X
10/20	X		

Satellite Image Dates for 2015

DATE	WESTCENTRAL	EASTCENTRAL	SOUTHEAST
04/02		X	
04/09	X		
05/27	X		
06/21		X	
06/30			X
07/16			X
07/23		X	
08/01			X
08/15	X		
08/24		X	
09/02			X
09/09		X	
09/26	X		
10/27		X	
11/03	X		

Table 2 – Image collection dates from the Landsat 5 imagery obtained from the SEO

For each LANDSAT zone, all the checked dates in Table 2 define the temporal distribution of NDVI measurements that are available for generating the crop NDVI time series reference curves.

5.1.2 Selection of Training Sites

Selection of irrigated parcel "training sites" is a key step in the crop typing process. The training sites are irrigated parcels with a crop type that has been assigned at a high-confidence level. This first and most important step involved creating NDVI reference curves for both the 2010 and 2015 irrigated parcel datasets. Initially, the irrigated parcel datasets (obtained from the SEO) were queried for any parcel where the crop type source was denoted as "field verified", where field verified means that the parcel's crop type was actually inspected and verified in the field by a CDWR employee. Querying the data resulted in, for example, 1,334 training sites out of 24,811 total parcels in the 2010 dataset. In Figure 21, the orange parcels represent the 2010 field verified potential training sites.

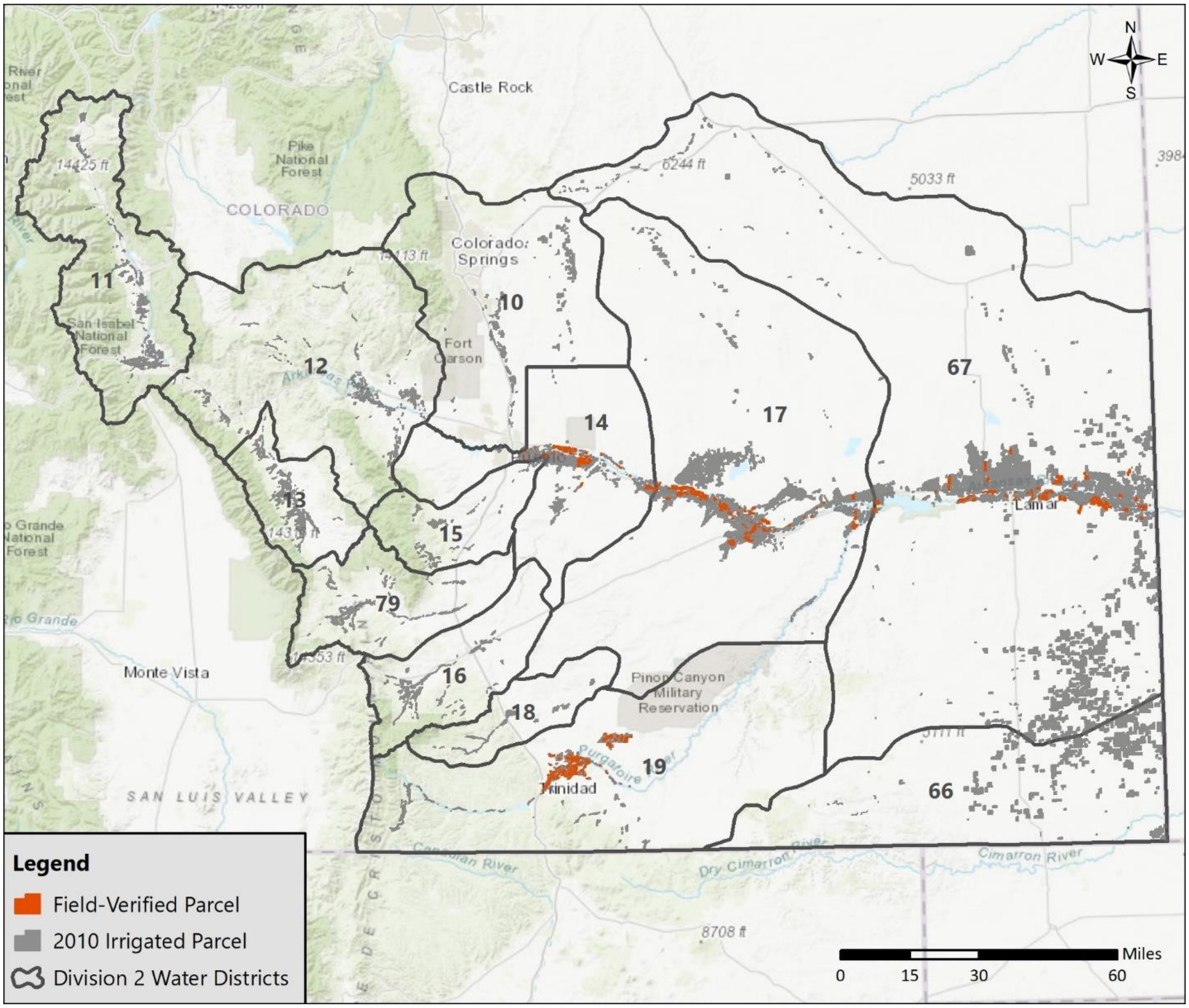


Figure 21 – Potential 2010 irrigated parcel training sites originally selected based on "field-verified" status of the parcels

Because the field-verified parcels were only located within the HIM area or the Purgatoire watershed (District 19), HRS judged that only using field-verified parcels as test sites was not spatially representative of the entire Division 2 irrigated area. To generate additional training sites, the 2010 and 2015 cropland data layer (CDL) developed and published by the USDA were evaluated and used as an additional source of training sites. (https://nassgeodata.gmu.edu/CropScape/). The USDA's CDL dataset is a 30-meter spatial resolution raster dataset that assigns a crop type or vegetation type to each raster pixel based on remote sensing techniques. The CDL is updated yearly and is available for Colorado for every year since 2008.

Zonal statistics, an ArcGIS tool described in a section above[7] was used to collect the *variety* statistic of the CDL dataset within each parcel in both the 2010 and 2015 datasets. The *variety* statistic measures the number of unique pixel values within each zone, or parcel, and assigns that value to the entire parcel. For example, if variety = 3 for a parcel, this indicates that 3 different crop type/vegetation pixels

[7] See ("Classify Each Parcels' Irrigated Status")

exist within that parcel's boundary. To qualify as a training site, HRS chose only those parcels with variety = 1, meaning that only 1 crop type was identified within the parcel boundary. After extracting qualified parcels, the CDL crop type was compared to the crop type assigned to the 2010 and 2015 datasets by the SEO to parcels that were not field-verified. If the CDL and SEO crop type agreed, then the parcel was retained as a training site. If the crop types did not agree, then the parcel was excluded. By selecting training sites using these criteria, not only did the number of training sites greatly increase, but the geographic extent of the training sites expanded and the variability of crop types increased (Figure 22).

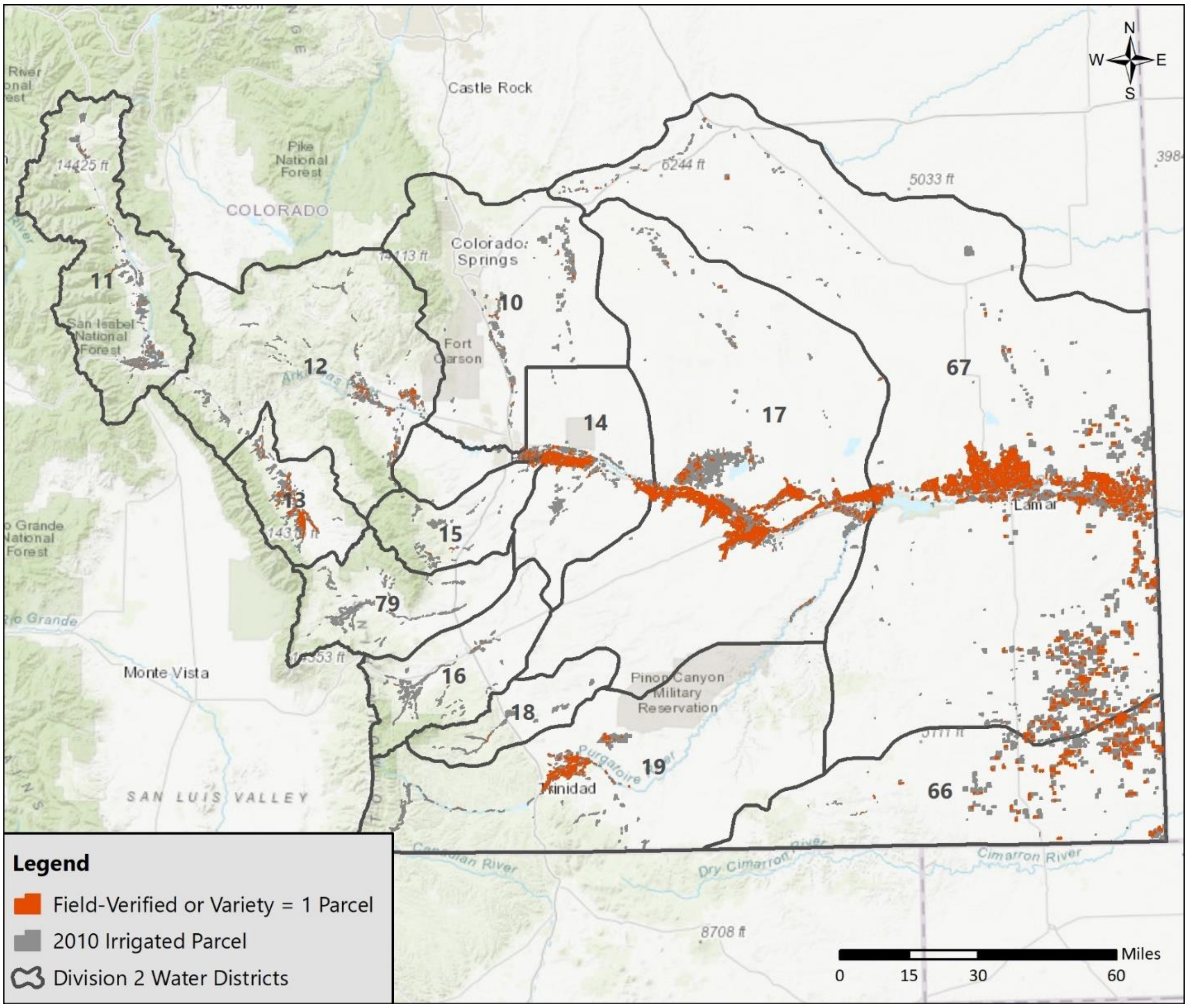


Figure 22 – 2010 irrigated parcel training sites selected using new criteria

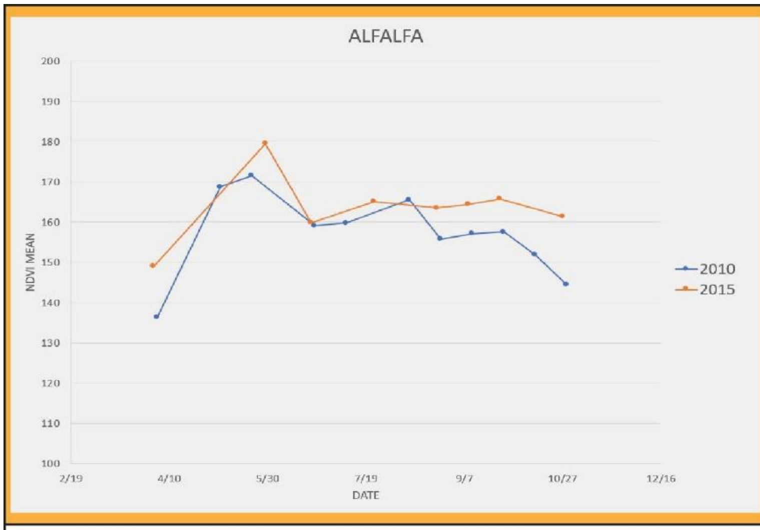
5.1.3 Time-Series NDVI Reference Curves

After field-verified and CDL-derived training sites were selected for both the 2010 and 2015 irrigated parcel datasets, NDVI reference curves were developed. The curve development process consisted of two main steps: (1) creating a "signature file" for each NDVI image; and, (2) inputting the data extracted from the signature file into MS Excel to graph the curve. Essentially, the signature file is an ascii file that describes the means and covariance of pixel values that are classified as a specific type (i.e. crop) of a raster dataset, in this case the raster datasets are the individual NDVI images. To create the signature file for each NDVI image, the tool Create Signatures, found in ArcMap's Spatial Analyst extension, was implemented. This tool required the NDVI image as well as the polygon shapefile of the training sites to be input. The mean from the output signature file for each NDVI image within each zone was then input into an MS Excel file and graphed according to the date of the image. The resultant graphs represent the NDVI temporal reference curve, or average growing pattern, for that particular crop within the specified growing period.

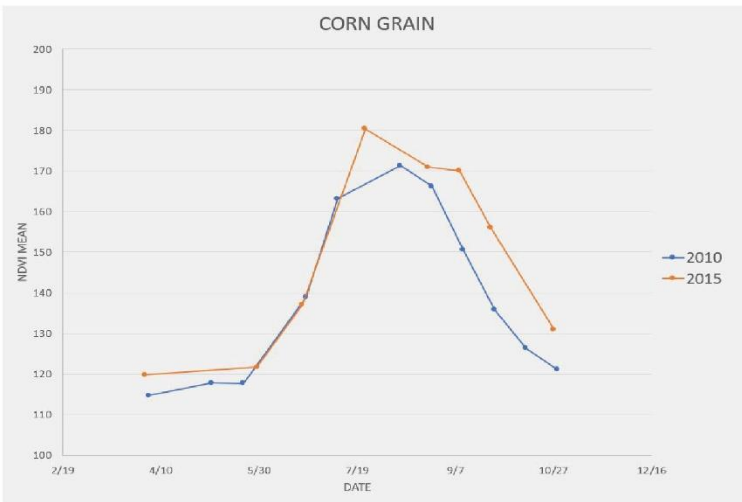
The temporal NDVI reference curves were evaluated by HRS' crop and consumptive use expert to verify that the reference curves were reasonably representative and indicative of the crop type that they represented. The curves displayed in the figures below show the temporal NDVI curves established with the data extracted from within the EastCentral zone. The visual evaluation confirmed that the pattern of each crop depicts the growing, irrigating, and harvesting habits of the crop with an overall agreement between the 2010 and 2015 growing patterns except for spring grain. The difference seen in spring grain, approximately from July to August, could be associated with the difference in dates that the signature files were collected. Figures 23-25 below display the NDVI temporal curves for each crop for the 2010 and 2015 growing seasons as well as a general description of each.

An NDVI reference curve was not developed for vegetables even though a small acreage of vegetables is grown in select areas of Division 2. This is due to the variability of growing patterns between the various crops included in the "vegetable" designation and the relatively small number of training sites. Since vegetables are only grown in certain areas, parcels with the vegetable crop type were hand-selected in a later crop-typing step, as discussed below.

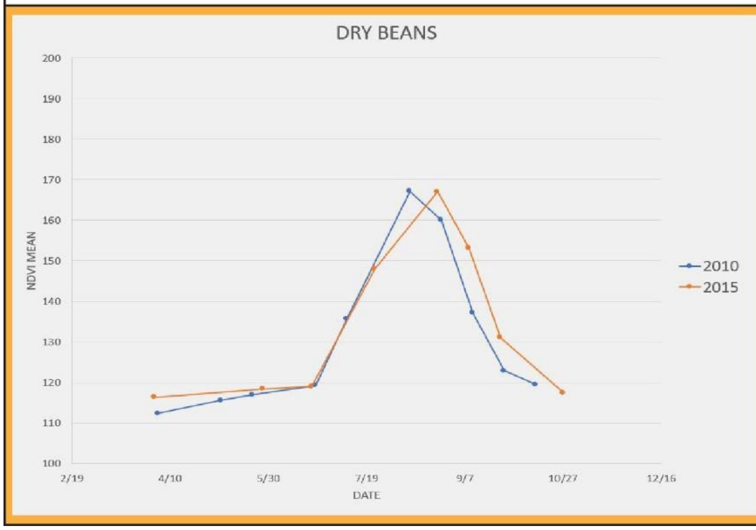
An NDVI reference curve was not developed for "no crop", with no crop meaning that the parcel was not irrigated. Parcels were designated as no crop through the irrigation status methods discussed in sections above.



Alfalfa begins to "green" up starting in springs and typically peaks in late May or June. The "greenness" drops off due to the first cutting, late May or early June, which often occurs at a similar time each growing season. After the first cutting, Alfalfa may have subsequent cuttings causing the NDVI indices to vary. The number of cuttings often depends on the availability of water to irrigate the crop.

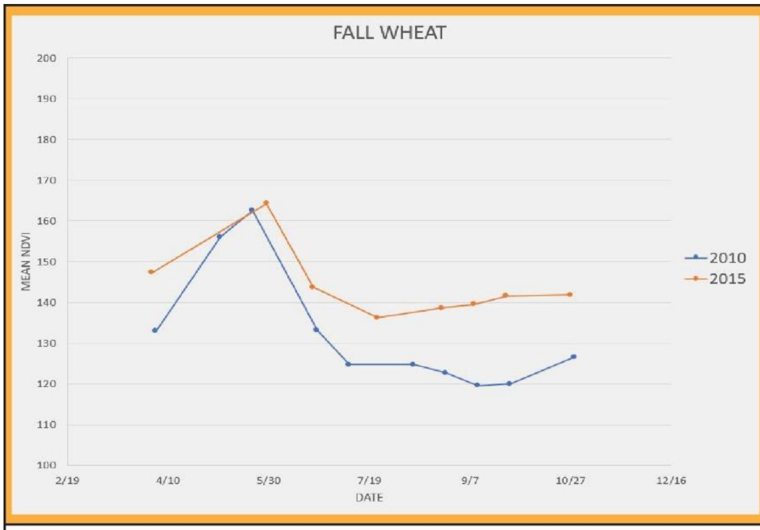


Corn is typically planted in May, then doesn't peak in "greenness" until July or August. Once corn reaches maturity, irrigation will cease in order to dry out the corn in preparation for fall harvest. The cessation of irrigation may cause the NDVI index value to slowly decline.

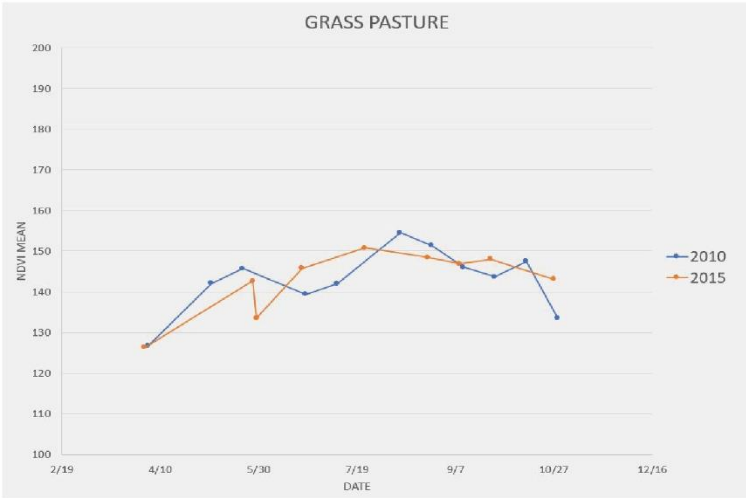


Dry beans are typically planted in late May to early June, then the plants are irrigated as they rapidly grow. Once dry beans hit maturity then irrigation will cease to allow the plants to dry out. Harvest occurs when the beans are dry.

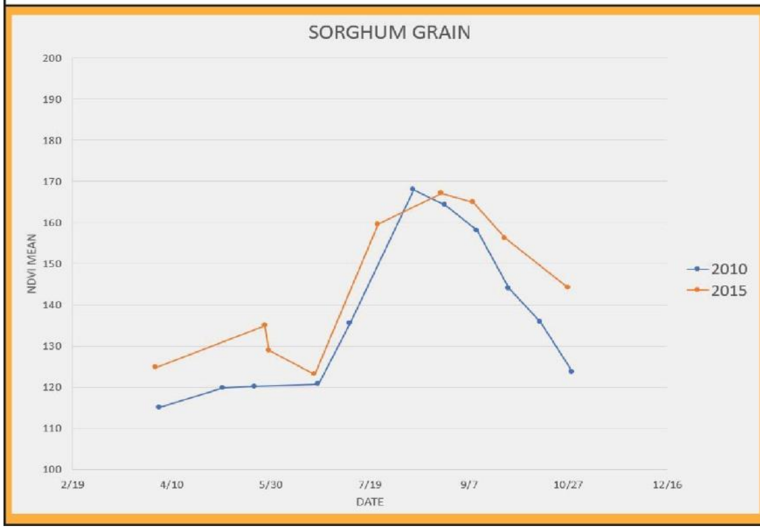
Figure 23 – Growing patterns for alfalfa, corn grain, and dry beans during the 2010 and 2015 growing seasons



Fall wheat is typically planted in September, then begins to green up in early spring with its established roots. Fall wheat grows and greens up rapidly, taking advantage of early spring moisture. Once the crop goes to grain irrigation tapers off and is harvested by mid-June or early July.

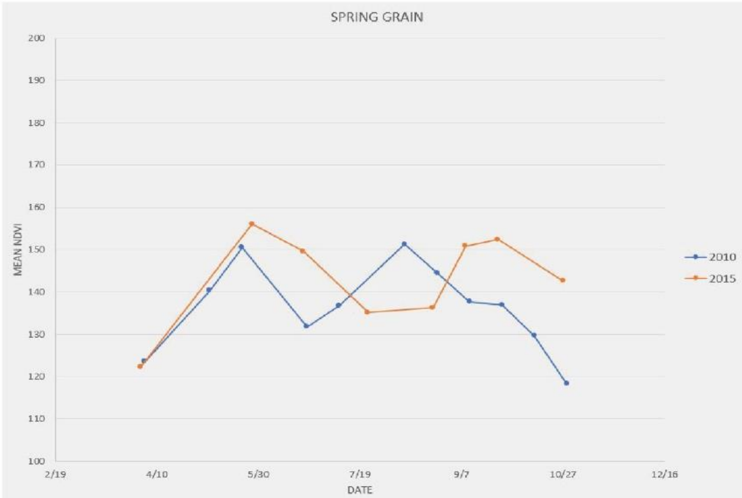


Grass pasture, or grass hay, typically has variable irrigation habits since it is not considered a cash crop. Grass could have multiple cuttings, however, in higher elevations there may only be one cutting in a growing season. Often times, if there is extra water available it will be applied to grass, but if not, then grass may not get much irrigation relative to other crops. Because of the growing, irrigating, and harvesting of this crop the NDVI temporal phenological curve may be inconsistent from year to year and other factors may need to be assessed to determine if a field is grass in the historic snapshots.



Sorghum grain is very similar to corn grain in growing and harvesting patterns, but may peak slightly later than corn. In general, more corn grain is grown within Division 2 than sorghum grain.

Figure 24 - Growing patterns for fall wheat, grass pasture, and sorghum grain during the 2010 and 2015 growing seasons



Spring grain is typically planted in the spring, possibly April, and grows rapidly until it obtains peak "greenness" in July or August. Usually, spring grain is only harvested, or cut, once for grain, but it may also be harvested for hay. The difference in uses for spring grain may account for the variability in the NDVI phenological curves.

Figure 25 - Growing patterns for spring grain during the 2010 and 2015 growing seasons

5.1.4 Test Curves for Separability

Once the NDVI reference curves were established and verified for the 2010 and 2015 datasets for each specific crop type, *a visual and numerical comparison* was made between the NDVI reference curves to assess two aspects of the data:

1. Whether the 2010 NDVI reference curves were similar enough to the 2015 NDVI reference curves. If the curves were dissimilar from each other, then the confidence level of using curves from one year to classify another year is lessened and another method would need to be established to crop type the irrigated parcel datasets.
2. Whether the NDVI reference curves for each crop type were different enough so that they could be distinguished and applied to the 1988 and 1998 datasets. If the NDVI reference curves for each crop were too similar, then it would be more difficult to distinguish between crop types through the MLC algorithm and another method would need to be established to crop type the irrigated parcel datasets.

The visual review confirmed that the NDVI reference curves display a distinguishable spectral-temporal similarity within the same crop during different growing seasons. However, there is a difference in the spectral-temporal pattern between different crop types. There are some crop types that are more similar in pattern than others, however, and this can be seen in Figure 26 below. The data show that corn grain and sorghum grain have similar growing patterns with their peak "greenness", or highest NDVI values, occurring at similar times in conjunction with a similar decline in NDVI value. This similarity was evident during the crop typing phase as these crops were the most difficult to distinguish. Other crops that were difficult to distinguish between included grass pasture and alfalfa, which was due to the variability in growth and cutting patterns as described in Figures 23 and 24 above.

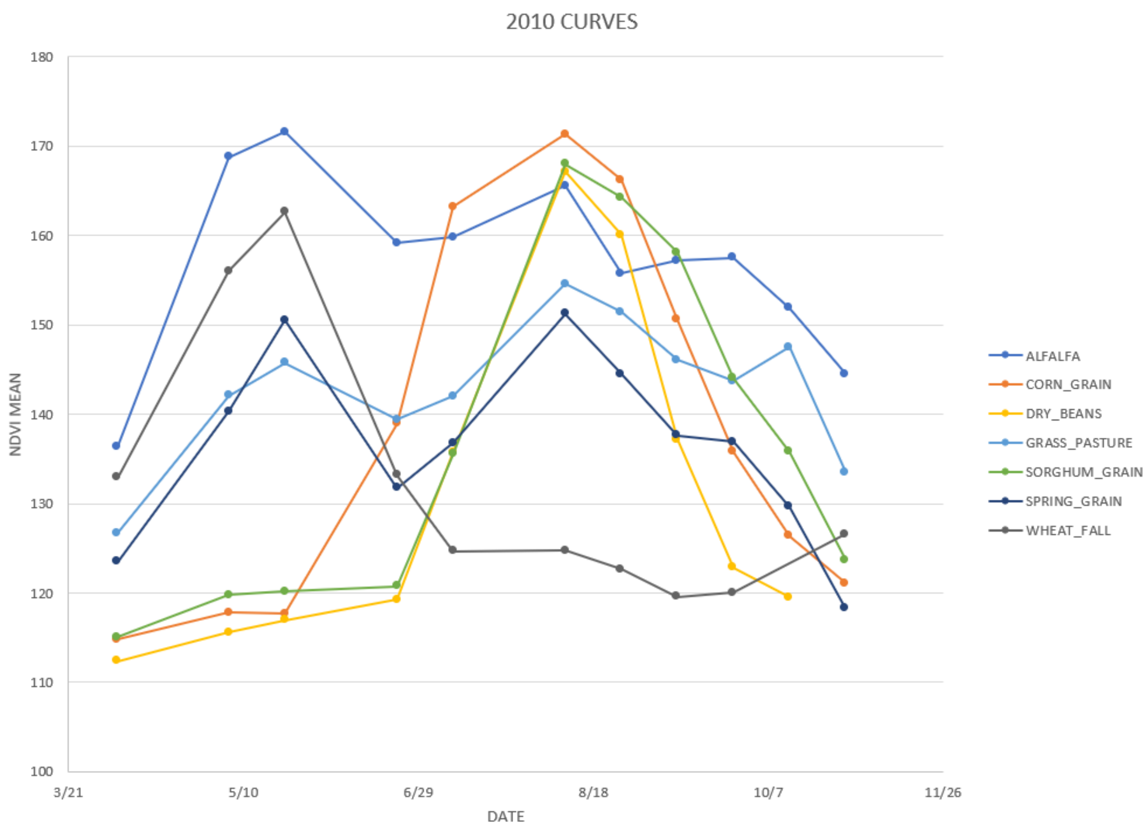


Figure 26 – NDVI temporal curves for seven main crops extracted from data during the 2010 growing season within the EastCentral zone

The numerical comparison consisted of calculating the JM statistic, which is a measure of the average distance between two probability spectral classes. The JM statistic gives a value between 0 and 2, where values near 0 indicate similarity and values near 2 indicate differences. For normally distributed classes[8], the JM distance is defined as:

$$J_{ij} = 2(1 - e^{-B_{ij}}),$$

Where:

J_{ij}=the JM distance between spectral classes i and j
B_{ij}=the Bhattacharyya Distance, which is defined as:

[8] The normality of the dataset is addressed below in the description of ArcGIS's maximum likelihood classifier (MLC)

$$B_{ij} = \frac{1}{8}(m_i - m_j)^T \left(\frac{C_i + C_j}{2}\right)^{-1} (m_i - m_j) + \frac{1}{2} ln\left(\frac{|(C_i + C_j)/2|}{\sqrt{|C_i C_j|}}\right),$$

Where:

m_i, m_j = means of class i and class j, respectively
C_i, C_j = variance of classes i and j, respectively

The JM statistic was first calculated for individual crop types located in the EastCentral Swath using the outputs of ArcGIS' create signatures for 2010 and 2015. To utilize the JM statistic without relying on interpolation, satellite imagery dates were compared and only images taken within five days of one another were assessed with the JM statistic. This was done with each crop type separately. For example, the JM statistic was used to determine the curve separability from the alfalfa 2010 dataset and the alfalfa 2015 dataset and was plotted alongside the 2010 and 2015 datasets (Figure 27).

The JM statistic was then calculated for different crops in the 2010 dataset to see if it could distinguish larger differences between crops in 2010 than it did between the same crops in 2010 and 2015. Figure 28 shows the JM distances between: a) fall wheat 2010 and 2015; b) corn grain 2010 and 2015; c) corn grain and fall wheat 2010; and, d) corn grain and fall wheat 2015. As shown, the differences between pairs of different crops are greater than the distances between pairs of same crops.

Figure 27 – The EastCentral zone 2010 and 2015 crop NDVI curves plotted alongside the JM distance

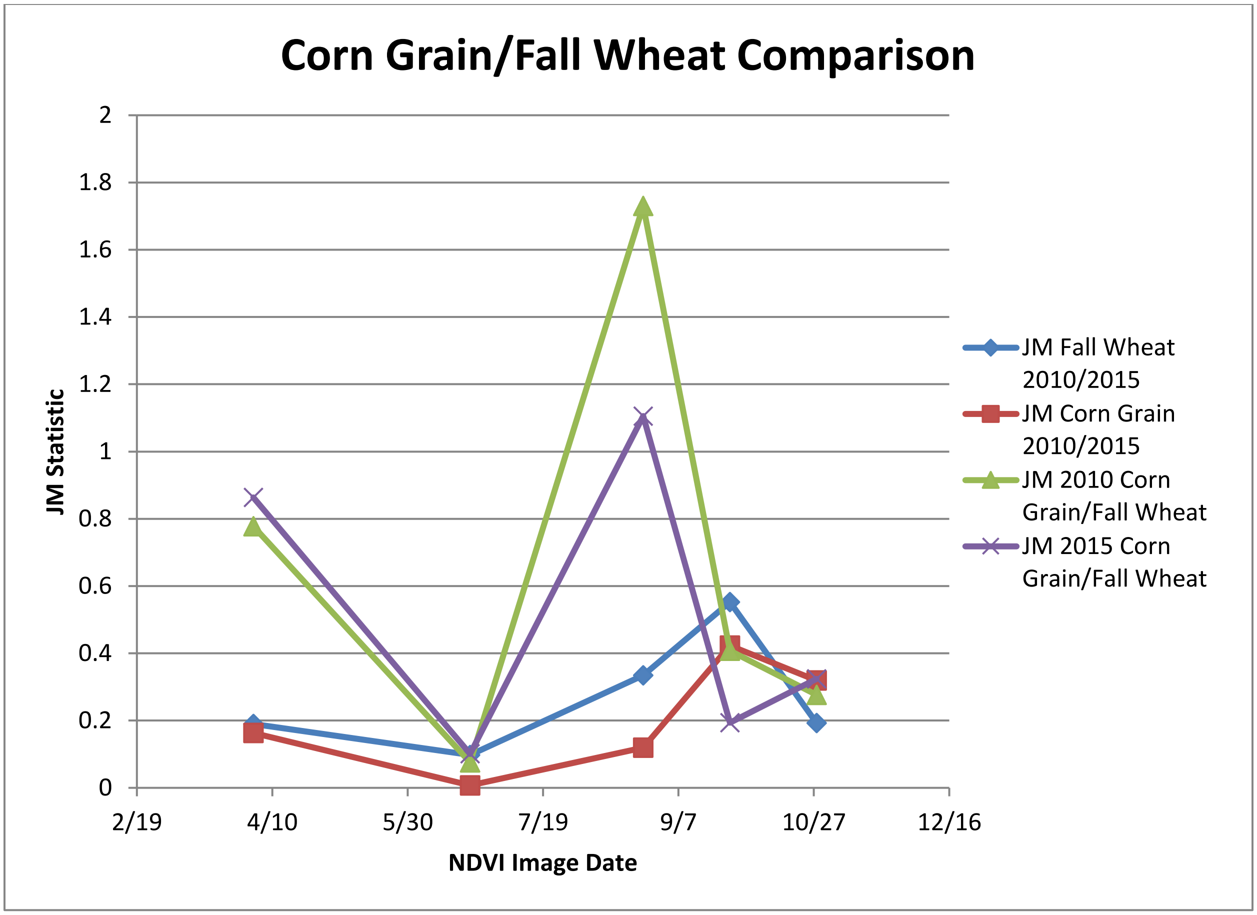


Figure 28 - The JM distances between fall wheat 2010 and 2015, corn grain 2010 and 2015, corn grain and fall wheat 2010, and corn grain and fall wheat 2015.

5.1.5 Develop District-Specific NDVI Reference Curves

The visual and numerical assessment of the NDVI reference curves for the 2010 and 2015 growing seasons suggested that the method of applying NDVI curve data from one growing year to another growing year could be carried out with favorable results. The next step was to further process the NDVI reference curves on a water district spatial resolution, rather than across the entire satellite image swath. This step allowed us to better account for localized variation in crop temporal NDVI signatures. The water district-specific NDVI reference curves were developed for the following districts (Figure 29): 10, 14, 15, 16, 17, 66 & 67 inside the HIM area, and 66 & 67 outside the HIM area. Districts 11, 12, 13, 18, and 79 were considered the “Elevation/Pivot” areas since these areas were classified based on a set of rules, rather than NDVI curve signatures. The Elevation/Pivot areas and classification methods are discussed in a section below.

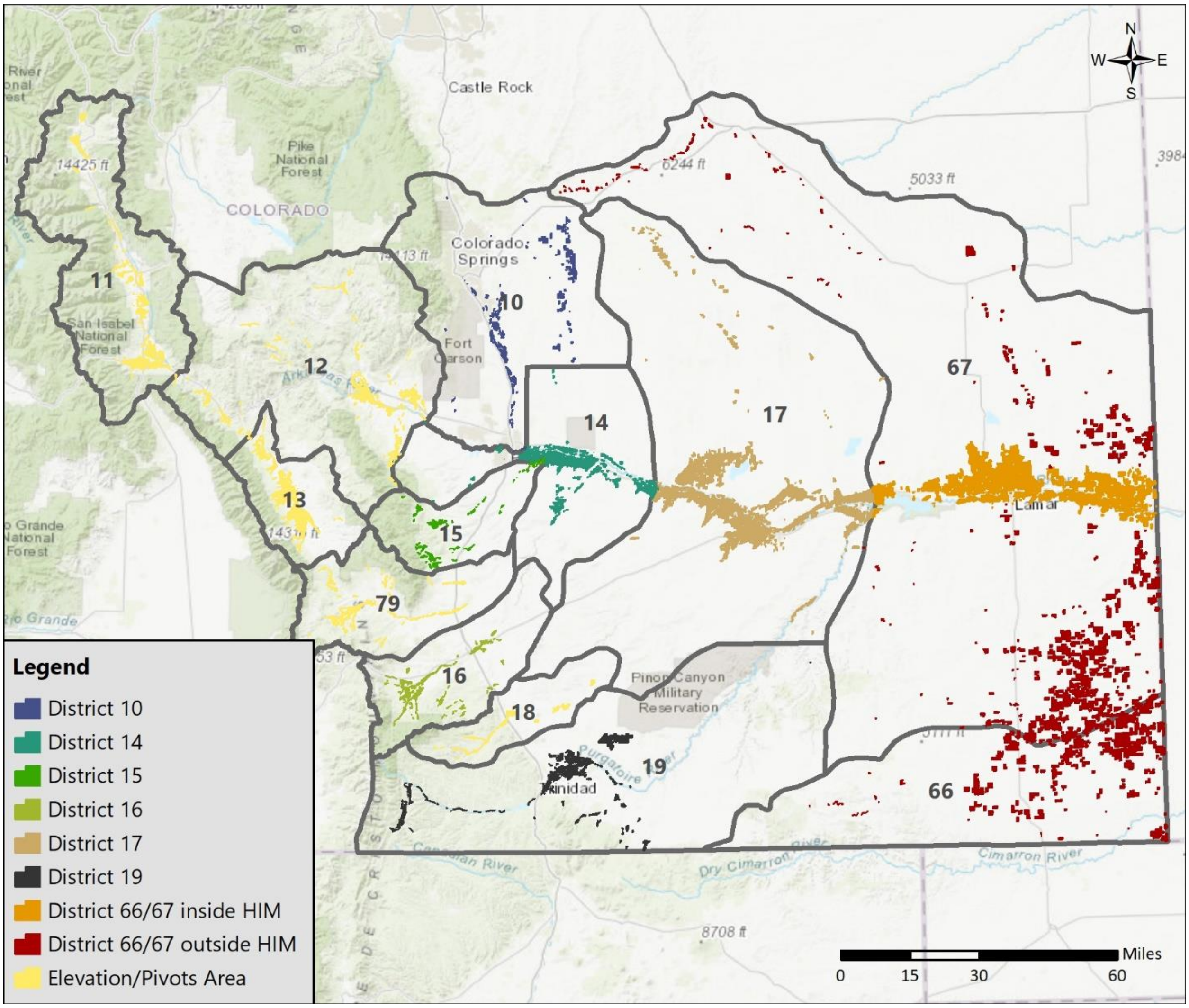


Figure 29 – Map showing how the districts were split up to develop the district-specific NDVI curves

The slight variations in NDVI reference curves due to localized conditions are apparent in Figure 30 below, which shows the NDVI reference curves for corn grain during the 2010 growing season in Districts 17, 19, 66/67 within the HIM area, and 66/67 outside the HIM area. These curves, though similar in overall growth pattern, exhibit slight differences in mean NDVI values as well peak "greenness" (i.e. point at which the NDVI value is at its maximum). Some of these variations may be due to differences in local harvesting schedules, slight climatic differences, or water source (i.e. well water versus ditch water). Creating water district specific NDVI reference curves to account for these slight differences produced a more accurate classification model as well as better defined post-classification rules.

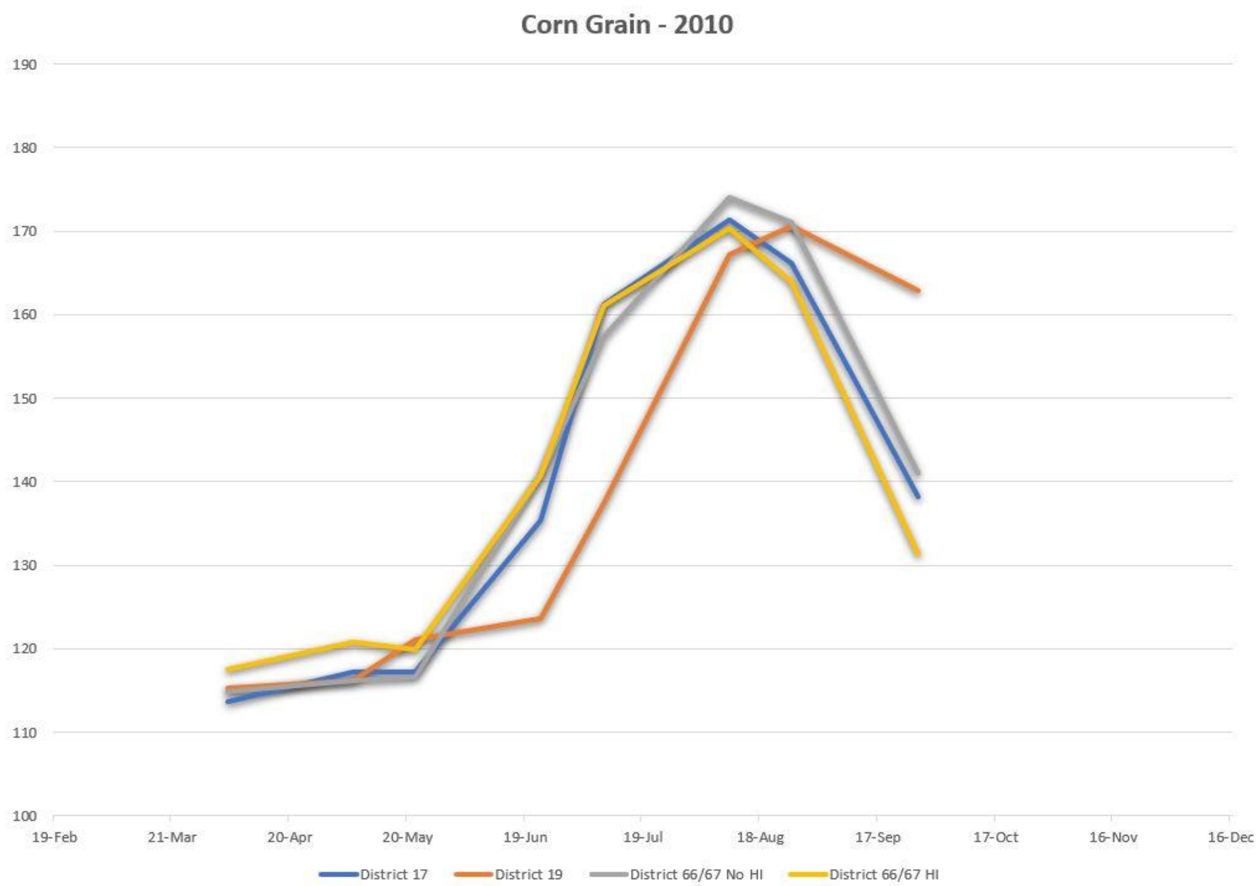


Figure 30 – NDVI signature curves for corn grain within 4 districts during the 2010 growing season

5.1.6 Apply NDVI Reference Curve Data with MLC Tool

The water district specific NDVI reference curve data developed through methods discussed above were used to re-classify, or crop type, the 2010 irrigated parcel dataset. This process was carried out for two purposes: 1) to test the accuracy of the NDVI reference curves and the working classification process; and, 2) to develop post-classification rules that would refine the classification of crops after the initial classification.

The method used to perform a test calibration crop typing for the 2010 irrigated parcel dataset, and ultimately crop type the 1988 and 1998 irrigated parcel datasets, was ArcMap's MLC tool. The MLC tool assumes that the NDVI data are normally distributed and works by classifying each pixel of an NDVI image using the mean vector and covariance matrix. Given these two properties for each pixel value within an NDVI image, ArcMap compute the statistical probability for each class, or crop type, to determine the classification of each pixel to a crop type. The MLC tool was carried out for each NDVI image date within each district.

The MLC tool output consists of a raster dataset with each pixel representing a class, or crop type (Figure 31). These data were further processed through ArcMap's zonal statistics tool (discussed in an earlier section). Through zonal statistics, the *mode* statistic was acquired for each parcel, meaning that the crop that was represented by the greatest count of pixels within a parcel boundary was assigned to that parcel for that NDVI collection date.

Figure 31 – Example of the raster dataset output after running ArcMap's MLC tool

The end result of this process was a series of tables with three pertinent pieces of information: (1) parcel unique numeric identifier; (2) assigned crop type; and, (3) date of satellite image collection. These output tables were compiled and input into MS Excel. Because each parcel in each district may have had up to 10 LANDSAT imagery collection dates, the final crop type was assigned to each parcel using the 'mode' statistic (i.e. the crop type that occurred most frequently for that parcel throughout the growing season).

5.1.7 Test Accuracy & Develop Post-Classification Rules

The crop typing accuracy for the 2010 dataset was assessed by evaluating the overall accuracy through an error matrix for each district. The overall accuracy essentially expresses, in percent, the proportion of sites that were classified accurately[9](that is, where the assigned crop type matched the training site crop type). The overall accuracy was calculated after the MLC tool classification, then again after crop typing rules were applied. The accuracy assessment suggested that with some general rules applied to how a crop type was assigned after the MLC tool application, the accuracy would only improve. A graph displaying the improvement in the overall accuracy for each district is shown in Figure 32. As shown, the accuracy improved by 5% to 30% before and after rules were applied to the crop typing process. Subsequently, district-specific rules were created such that the crops were more accurately assigned to

[9] Remote Sensing and Image Interpretation, Lillesand et al, 2008

each parcel and these rules were used as guides during the crop typing process for the 1998 and 1988 irrigated parcel datasets.

Some of examples of the rules include:

- IF 07.16.10 and 08.01.10 were both classified as “corn grain”, then final crop type = *corn grain*
- IF mode = “fall wheat”, then final crop type = *fall wheat*
- IF crop is classified as dry beans by MLC on more than 2 dates, then final crop type = *dry beans*
- IF 04.27.10, 05.29.10, and 06.30.10 were classified as “grass pasture”, then final crop type = *grass pasture*

> These rules may have been adjusted in the 1988 and 1998 irrigated parcel datasets to better represent the county crop statistics.

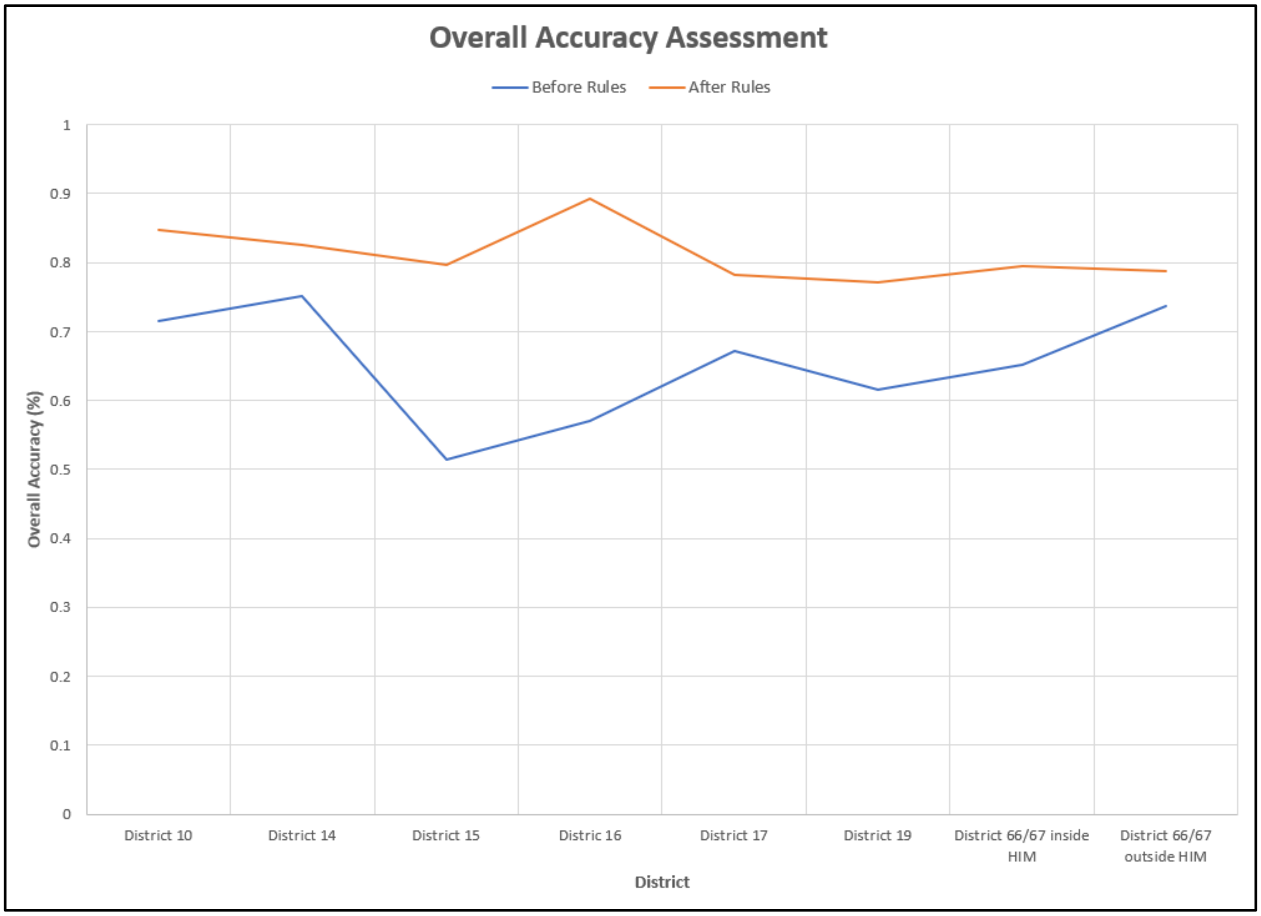


Figure 32 – Graph displaying the overall accuracy values before and after rules were applied to the crop typing process

5.1.8 Crop Type 1988 and 1998 Datasets

Crop typing of the 1988 and 1998 irrigated parcel datasets followed a 3-step approach, as shown in Figure 33. The first step was to apply the district specific NDVI signature curves with the MLC tool in the same manner as described in the above section entitled *Apply NDVI Reference Curve Data with MLC Tool*. The next step was to apply the post-classification rules as discussed in the above section. The final tier was to make the small manual adjustments to better correlate the final crop type data to the county crop statistics.

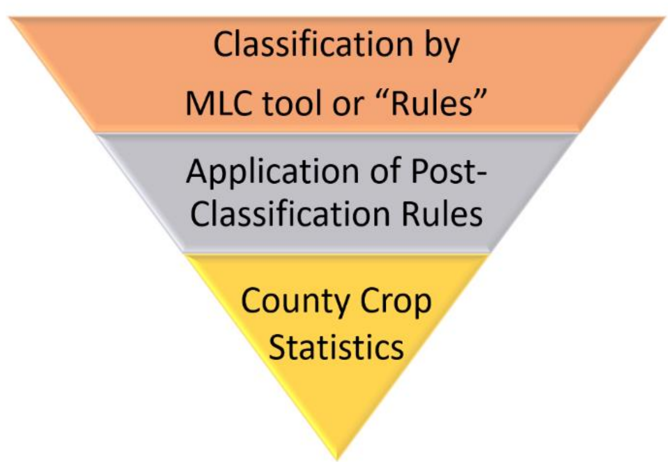


Figure 33 – The general 3-tier approach to crop-typing the 1998 and 1988 irrigated parcel datasets

Some districts such as 11, 12, 13, 18, and 79 have a limited variety of crops grown and irrigated, mainly consisting of alfalfa and grass pasture. This limited variety of crops can be associated with the elevation, topography, soils, and weather within these districts. Therefore, these districts were not included in the crop typing process as discussed above. Instead, a set of rules only were applied to the parcels within these districts to classify the crop type. The rules include:

- If mean elevation of the parcel is > 6,500 feet above mean sea level, then it is grass pasture
- If irrigation type in a parcel is a sprinkler, then it is alfalfa

5.1.9 County Crop Statistics

The final phase of the crop typing process, which also served as a QC check, was to compare the crop type outputs of each county with the county crop statistics for that snapshot year. County crop statistics are published by the USDA on a yearly basis and give an estimated amount of acreage of each crop type irrigated by county for the State of Colorado. In general, the total amount of acreage designated as irrigated in the 1988 and 1998 snapshots was larger than what was reported in the county crop statistics. One reason for this difference could be attributed to the county crop statistics only reporting acreage harvested rather than acreage irrigated. An exception to this was in Baca and Bent counties in the 1988 snapshot. Overall, these two counties reported more acreage in the county crop statistics than in the snapshots. To adjust for this, the NDVImax threshold value was decreased slightly within those two counties only so that additional acreage was designated as irrigated in the irrigated parcel snapshot.

> The NDVImax mean values for each parcel are included in the 1998 and 1988 irrigated parcel dataset attribute tables.

Because the total irrigated acreage amounts did not match perfectly, the ratios (as percentages) of each crop within each county were compared. If the crop ratio differed by more than 7% between the irrigated parcel datasets and the county crop statistics, then crop types were manually adjusted to bring those comparative ratios closer together. The manual adjustments were not arbitrary, but instead, followed a set of established guidelines. Some of these guidelines included:

- Only switch crops that exhibit similar NDVI curve signatures (i.e. corn grain and sorghum grain)
- Only manually adjust crops that are historically grown in the area (i.e. dry beans would not be manually input into an area where only grass pasture is grown)

After manually adjusting to better match the county crop statistics, vegetables were added into the irrigated parcel datasets. As stated above, vegetables were not part of the crop typing process due to the variability of growing patterns between the various crops included in the “vegetable” designation. To add vegetables back into the irrigated parcel datasets, the centroid of vegetable parcels were extracted from the master parcel dataset. The centroids were then spatially joined in ArcGIS to the 1998 irrigated parcel dataset and those joined parcels that were designated as irrigated were assigned to vegetables. This same process was followed for the 1988, 1975, and 1954 snapshots.

Also, those parcels designated as drip irrigation due to the presence of orchards and tree farms in the aerial imagery were manually designated as 'orchard' for the crop type even though county crop statistics did not include orchard in its evaluation.

The tables below show the comparison between the irrigated parcel crop types and county crop statistics for 1998 and 1988 for major counties in Division 2.

1998 Baca County

	Derived by MLC Classification		County Crop Statistics	
Crop Type	Acres	% of Whole County	Acres	% of Whole County
ALFALFA	12,146	13.4%	6,300	8.8%
CORN GRAIN	35,916	39.7%	32,500	45.6%
GRASS PASTURE	7,947	8.8%	1,400	2.0%
SORGHUM GRAIN	12,187	13.5%	10,000	14.0%
FALL WHEAT	22,224	24.6%	21,000	29.5%

1988 Baca County

	Derived by MLC Classification		County Crop Statistics	
	Acres	% of Whole County	Acres	% of Whole County
ALFALFA	4,063	7.5%	2,500	4.8%
CORN GRAIN	10,656	19.6%	9,500	18.2%
GRASS PASTURE	4,026	7.4%	2,800	5.4%
SORGHUM GRAIN	14,747	27.1%	17,200	32.9%
SPRING GRAIN	432	0.8%	300	0.6%
FALL WHEAT	20,475	37.6%	20,000	38.2%

1998 Bent County

	Derived by MLC Classification		County Crop Statistics	
Crop Type	Acres	% of Whole County	Acres	% of Whole County
ALFALFA	33,752	54.4%	33,700	59.5%
CORN GRAIN	15,901	25.6%	14,700	26.0%
GRASS PASTURE	5,514	8.9%	4,200	7.4%
SORGHUM GRAIN	1,078	1.7%	1,000	1.8%
FALL WHEAT	5,844	9.4%	3,000	5.3%

1988 Bent County

	Derived by MLC Classification		County Crop Statistics	
Crop Type	Acres	% of Whole County	Acres	% of Whole County
ALFALFA	27,021	47.3%	28,000	48.4%
DRY BEANS	215	0.4%	200	0.3%
CORN GRAIN	9,229	16.2%	8,200	14.2%
GRASS PASTURE	4,345	7.6%	3,500	6.0%
SORGHUM GRAIN	7,948	13.9%	8,200	14.2%
SPRING GRAIN	755	1.3%	800	1.4%
FALL WHEAT	7,601	13.3%	9,000	15.5%

1998 Chaffee County

	Derived by MLC Classification		County Crop Statistics	
Crop Type	Acres	% of Whole County	Acres	% of Whole County
ALFALFA	6,116	35.8%	7,000	41.2%
GRASS PASTURE	10,946	64.2%	10,000	58.8%

1988 Chaffee County

	Derived by MLC Classification		County Crop Statistics	
Crop Type	Acres	% of Whole County	Acres	% of Whole County
ALFALFA	2,117	13.3%	6,000	30.0%
GRASS_PASTURE	13,769	86.7%	14,000	70.0%

1998 El Paso County

Crop Type	Derived by MLC Classification		County Crop Statistics	
	Acres	% of Whole County	Acres	% of Whole County
ALFALFA	8,959	67.6%	6,000	61.2%
GRASS PASTURE	3,733	28.2%	3,000	30.6%
SORGHUM GRAIN	348	2.6%	300	3.1%
FALL WHEAT	218	1.6%	500	5.1%

1988 El Paso County

Crop Type	Derived by MLC Classification		County Crop Statistics	
	Acres	% of Whole County	Acres	% of Whole County
ALFALFA	6,747	61.8%	5,000	58.8%
CORN GRAIN	294	2.7%	500	5.9%
GRASS PASTURE	2,675	24.5%	2,700	31.8%
FALL WHEAT	1,195	11.5%	300	3.5%

1998 Fremont County

Crop Type	Derived by MLC Classification		County Crop Statistics	
	Acres	% of Whole County	Acres	% of Whole County
ALFALFA	8,069	60.3%	6,800	61.8%
CORN GRAIN	974	7.3%	1,000	9.1%
GRASS PASTURE	4,067	30.4%	3,200	29.1%
VEGETABLES	6	0.0%	0	0.0%
ORCHARD	268	2.0%	0	0.0%

1988 Fremont County

Crop Type	Derived by MLC Classification		County Crop Statistics	
	Acres	% of Whole County	Acres	% of Whole County
ALFALFA	7,603	61.1%	5,500	53.9%
CORN GRAIN	222	1.8%	200	2.0%
GRASS PASTURE	4,313	34.7%	4,500	44.1%
VEGETABLES	15	0.1%	0	0.0%
ORCHARD	292	2.3%	0	0.0%

Table 3 – Comparison between crop types derived from NDVImax-MLC classification and the USDA county crop statistic.

1998 Otero County

Crop Type	Derived by MLC Classification: Acres	Derived by MLC Classification: % of Whole County	County Crop Statistics: Acres	County Crop Statistics: % of Whole County
ALFALFA	26,162	37.5%	19,300	38.2%
DRY BEANS	837	1.2%	900	1.8%
CORN GRAIN	26,205	37.6%	19,800	39.2%
GRASS PASTURE	6,624	9.5%	3,000	5.9%
SORGHUM GRAIN	828	1.2%	300	0.6%
SPRING GRAIN	1,301	1.9%	1,200	2.4%
VEGETABLES	1,768	2.5%	0	0.0%
FALL WHEAT	6,048	8.7%	6,000	11.9%

1988 Otero County

Crop Type	Derived by MLC Classification: Acres	Derived by MLC Classification: % of Whole County	County Crop Statistics: Acres	County Crop Statistics: % of Whole County
ALFALFA	24,727	38.3%	23,400	46.9%
DRY BEANS	1,233	1.9%	1,200	2.4%
CORN GRAIN	20,843	32.3%	17,000	34.1%
GRASS PASTURE	7,801	12.1%	2,800	5.6%
SORGHUM GRAIN	951	1.5%	1,000	2.0%
SPRING GRAIN	0	0.0%	800	1.6%
VEGETABLES	1,545	2.4%	0	0.0%
FALL WHEAT	7,469	11.6%	3,700	7.4%

1998 Prowers County

Crop Type	Derived by MLC Classification: Acres	Derived by MLC Classification: % of Whole County	County Crop Statistics: Acres	County Crop Statistics: % of Whole County
ALFALFA	85,139	63.1%	56,500	58.9%
CORN GRAIN	24,438	18.1%	21,100	22.0%
GRASS PASTURE	3,098	2.3%	3,000	3.1%
SORGHUM GRAIN	3,263	2.4%	3,500	3.6%
SPRING GRAIN	338	0.3%	300	0.3%
VEGETABLES	356	0.3%	0	0.0%
FALL WHEAT	18,322	13.6%	11,500	12.0%

1988 Prowers County

Crop Type	Derived by MLC Classification: Acres	Derived by MLC Classification: % of Whole County	County Crop Statistics: Acres	County Crop Statistics: % of Whole County
ALFALFA	52,554	48.4%	52,000	51.7%
DRY BEANS	523	0.5%	500	0.5%
CORN GRAIN	12,007	11.1%	12,000	11.9%
GRASS PASTURE	6,268	5.8%	2,400	2.4%
SORGHUM GRAIN	14,586	13.4%	15,700	15.6%
VEGETABLES	324	0.3%	0	0.0%
SPRING GRAIN	4,067	3.7%	3,900	3.9%
FALL WHEAT	18,264	16.8%	14,000	13.9%

1998 Pueblo County

Crop Type	Derived by MLC Classification: Acres	Derived by MLC Classification: % of Whole County	County Crop Statistics: Acres	County Crop Statistics: % of Whole County
ALFALFA	16,773	47.7%	15,000	54.5%
DRY BEANS	2,783	7.9%	1,800	6.5%
CORN GRAIN	6,628	18.8%	6,300	22.9%
GRASS PASTURE	6,563	18.6%	3,700	13.5%
SORGHUM GRAIN	1,138	3.2%	200	0.7%
SPRING GRAIN	11	0.0%	0	0.0%
VEGETABLES	797	2.3%	0	0.0%
FALL WHEAT	507	1.4%	500	1.8%

1988 Pueblo County

Crop Type	Derived by MLC Classification: Acres	Derived by MLC Classification: % of Whole County	County Crop Statistics: Acres	County Crop Statistics: % of Whole County
ALFALFA	10,887	31.4%	12,000	37.9%
DRY BEANS	2,133	6.2%	1,900	6.0%
CORN GRAIN	12,206	35.2%	11,000	34.7%
GRASS PASTURE	5,764	16.6%	4,000	12.6%
SORGHUM GRAIN	1,544	4.5%	1,100	3.5%
VEGETABLES	810	2.3%	400	1.3%
SPRING GRAIN	425	1.2%	0	0.0%
FALL WHEAT	901	2.6%	1,300	4.1%

Table 4 - Comparison between crop types derived from NDVImax-MLC classification and the USDA county crop statistic.

5.2 Crop-Type Irrigated Parcels (pre-1985)

A basic crop typing approach for the 1954 and 1975 irrigated parcel datasets was taken because crop type data was very limited at best. The method for applying crops to pre-1985 datasets was to simply apply the crop types from the 1988 irrigated parcel dataset to 1975, then manually apply crops to parcels that may have been delineated in 1975, but not in 1988. This same process was followed for the 1954 irrigated parcel dataset, except that the 1975 crop types were applied. Steps taken for this process included:

- Generate centroids for all irrigated parcels in 1988 or 1975.
- In ArcGIS, spatially join those centroids using the "Within A Distance" match option to the 1975 or 1954 irrigated parcel dataset.
- Query those parcels that had an irrigation status of "YES", but no associated crop, or centroid attached.
- Assign crop types to those parcels according to what is "typically" grown in the area.
- Spatially join the vegetable centroids (discussed above) to the parcels and re-assign those parcels as "Vegetable".
- Assign any parcel with 'drip' as irrigation status "Orchard".
- Finally, all parcels with an irrigation status of "NO" had a crop type designated as "No_Crop".

6.0 IRR Code Update

The final revision made to the irrigated parcel datasets was to update the IRR code in the attribute tables. The IRR code is unique to the Arkansas River Basin datasets and provides a water use or source description for each parcel, such as when a parcel is only irrigated with surface water, or when a parcel may be irrigated with both groundwater and surface water. Five codes were used:

- G – groundwater only
- S – surface water only
- B – both groundwater and surface water
- N – parcel was not irrigated during that growing season
- O – no water source is associated with parcel

IRR Code 'O', denoting 'orphaned' parcels, was added to the original code list used in the master parcel dataset for this task. An orphaned irrigated parcel means that no water source is assigned. One reason why no water source is assigned is that groundwater sources that may have been assigned to the master parcel dataset may not have existed during the snapshot year, therefore removed during the groundwater source removal task discussed above.

The dry-up code (D) was not assigned since the historic dry-up parcels are currently only preliminary and require review by DWR and/or CWCB staff. The parcels that are discussed in the dry-up section above were noted in the attribute table as potentially being a dry-up parcel. The IRR code assignment for those parcels followed the same methodology as discussed herein.

The IRR code was assigned by the attribute queries listed below:

- If parcel is irrigated and contains only a groundwater source (GWDID), then IRR code = G.
- If parcel is irrigated and contains only a surface water source (SWDID), then IRR code = S.
- If parcel is irrigated and contains both a groundwater and surface water source (GWDID and SWDID), then IRR code = B.
- If parcel is not irrigated, the IRR code = N.
- If parcel has neither a surface water nor a groundwater source assigned, then IRR code = O.

Some parcels may have both surface water and groundwater associated with it. In many cases it is possible that these parcels with dual water sources only use one source for irrigation during a particular year. HRS did not take into consideration any diversion or pumping records when assigning the IRR code. The original IRR code assigned in the master parcel dataset was retained in the irrigated parcel dataset attribute tables for opportunity to cross-reference.

The query above took into consideration the historic wells that were either automatically or manually assigned to parcels as discussed in the section above, "Add Historic Groundwater Sources to Snapshot Years, as Necessary".

7.0 DATA CONSIDERATIONS

As with any project of this size and type, there are data considerations and limitations stemming from the complex technical methodology, required degree of human-judgement, complexity of the natural environment, and limitations of the data. Any assumptions inherently built into the master parcel dataset will have been carried through to the four snapshot datasets produced by this project. The general philosophy when building these snapshots was: "add parcels, and do not delete (without good reason)".

Irrigated status for the 1988 and 1998 snapshots was determined by the NDVI data provided by the SEO. As mentioned previously, the NDVI threshold for a field to be considered irrigated basin-wide was 150 (and adjusted for Baca and Bent counties in 1988 as discussed previously). Similar projects that have determined irrigated status from NDVI data have used a varied approach, going so far as to customize the NDVI threshold for each individual field, usually varying from 120 to 170. However, this approach requires much more data on individual fields or areas. The static NDVI approach used here, while less time consuming, may irrigate more fields in wet areas like District 13, and less fields in typically drier areas. But it is accepted that if a field is above the 150 NDVI threshold, it is very likely irrigated.

Image quality sometimes played a role in the quality of digitization and/or determination of irrigated status (pre-1985). And, to couple with the image quality, sometimes the photo date year of the image varied from the snapshot year it was supposed to represent. This was because in some areas of the basin the only image available may not have matched the snapshot year. These factors were taken into consideration when digitizing and determining irrigated status of the parcels. See the ArkDSS Task 1.2 Memorandum (Historical Air Photos) for more details.

The calendar month that the image was acquired during the snapshot year also proved to be crucially important for determining irrigated status in the pre-1985 snapshots. It is easier to see signs of irrigation in a photo that is acquired in July, the height of the irrigation season, than it is in a photo acquired in November, usually after all irrigation has ceased. This affects the primary method of determining irrigated status visually.

8.0 DATA DELIVERABLES

The ArkDSS Subtask 1.3 scope of work specifies the following deliverables:

- Up to five historical irrigated acreage snapshots
- A Task 1.3 Technical Memorandum (this document)
- Electronic files produced as intermediate and final steps to generating the final GIS coverages

The datasets delivered along with this Technical Memorandum include:

- Four historical irrigated parcel datasets
    - These datasets are polygon feature classes saved inside a geodatabase and include:
        1. **IrrigParcels_98: 1998 irrigated parcel dataset**
        2. **IrrigParcels_88: 1988 irrigated parcel dataset**
        3. **IrrigParcels_75: 1975 irrigated parcel dataset**
        4. **IrrigParcels_54: 1954 irrigated parcel dataset**
    - Attributes associated with the datasets are included in Attachment A.
    - Metadata for the above datasets

- Eight historical well datasets
    - These datasets are point feature classes saved inside a geodatabase. They represent the historic wells that were applied to the irrigated parcel datasets going back in time. The field 'ET_Status' in the attribute table was assigned to either ***A***, meaning that the well was manually attributed to the parcel; ***NA***, meaning that the well was not attributed to any parcel; or ***Snapped***, meaning that the well was automatically snapped to a nearby parcel with the ET Geo Wizards tool, *Global Snap Points*
    - The datasets include:
        1. **Wells_InsideHI_1954: Historic wells drilled before 1954 located inside the HIM**
        2. **Wells_InsideHI_1975: Historic wells drilled before 1975 located inside the HIM**
        3. **Wells_InsideHI_1988: Historic wells drilled before 1988 located inside the HIM**
        4. **Wells_InsideHI_1998: Historic wells drilled before 1998 located inside the HI**
        5. **Wells_OutsdieHI_1954: Historic wells drilled before 1954 located mainly outside the HIM with some located inside**
        6. **Wells_OutsideHI_1975: Historic wells drilled before 1975 located mainly outside the HIM with some located inside**
        7. **Wells_OutsideHI_1988: Historic wells drilled before 1988 located mainly outside the HIM with some located inside**
        8. **Wells_OutsideHI_1998: Historic wells drilled before 1988 located mainly outside the HIM with some located inside**
    - The original source of these eight datasets were the historic well shapefiles submitted to HRS by the SEO and Division 2 called, "Well_List_Inside_HI" (Division 2) and "Well_List_Outside_HI" (SEO)

- Signature files used to create the NDVI reference curves
    - The signature files were extracted with ArcMap's 'Create Signatures' tool using the 2010 NDVI images on a district-by-district basis
    - The signature files are asci-based files and are saved with district number and collection day of the satellite image (i.e. District10_0427.gsg is the signature file for District 10 collected on April 27, 2010)
    - The signature files are saved in the following file folders:
        1. District_10
        2. District_12
        3. District_14
        4. District_15
        5. District_16
        6. District_17
        7. District_19
        8. District_6667_NoHI: For use on parcels within districts 66 and 67 outside of the HIM and inside the "EastCentral" zone only
        9. District_6667_HI: For use on parcels within districts 66 and 67 inside the HIM and inside the "EastCentral" zone only
        10. District_6667_HI_SE: For use on parcels within districts 66 and 67 inside the HIM and within the "SouthEast" zone only
        11. District_6667_NoHI_SE: For use on parcels within districts 66 and 67 outside the HIM and within the "SouthEast" zone only

9.0 REFERENCES

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