Improving Cadastre: Development of a Workflow Prototype Utilizing ESRI's Parcel Fabric

Abstract

The Rapid City/Pennington County, South Dakota, GIS Division has continuously maintained a parcel dataset that was originally created in 1989. Since its development, it has gone through many different conversion processes and been hosted on several different software platforms. Advances in technology and the desire to expand the use of land based information (some of which requires highly accurate data) highlighted the need to improve the community's cadastre. Technical obstacles, such as incorporating and maintaining survey information as well as easily updating related layers, previously hindered this effort. These obstacles seem to have been addressed by Environmental Systems Research Institute's (ESRI) parcel fabric data model and are the focus of this project.

This study focused on several key factors that are important to the stakeholders involved and include (1) developing a feasible workflow for converting existing data (2) maintaining and improving the integrity of cadastre data over time and (3) integrating these data with related data layers. To examine the feasibility of utilizing the parcel fabric, this project developed a workflow prototype that was evaluated while testing a representative sample area in Rapid City. The results from this study were used to identify best-practices that will be applied when working with the county-wide dataset.

1 Background

The City of Rapid City, South Dakota, is located on the eastern flank of the Black Hills uplift in Pennington County, and is home to approximately 70,000 people (Figure 1). A much larger population is served by the community, however, because of tourism and the regional amenities provided by the City.

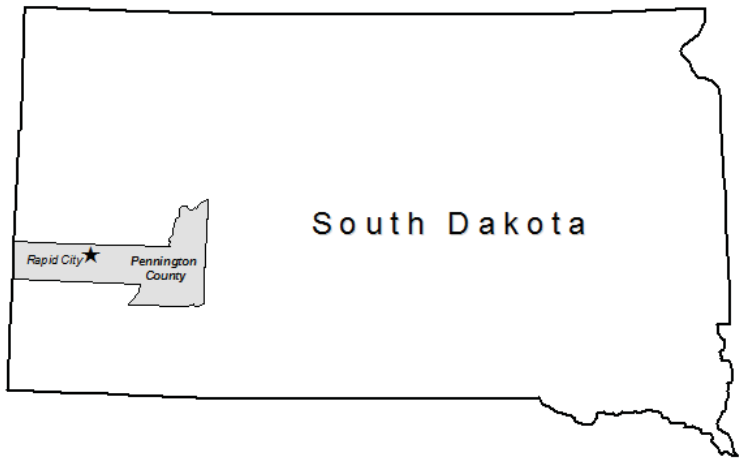


Figure 1. Vicinity map illustrating Rapid City's location in South Dakota.

Not unlike other regions similar in size, GIS has been implemented to help maintain and manage assets. To maximize resources, the City of Rapid City's GIS Division was developed as a joint venture between the Pennington County and Rapid City governments and is responsible for maintaining common base data layers such as street centerlines, address points, aerial photography, zoning and a cadastre or land registry/tax parcels. A cadastre as defined by Robillard et al. (2011) is "an official register of the quantity, value and ownership of real estate used in apportioning taxes" and the land parcel is an individual unit within the cadastre on which the identification of land rights resides (Enemark 2010). For the remainder of this paper, parcels and cadastre will be used interchangeably and for the purposes of this study references will be made exclusively to Rapid City.

Rapid City uses its parcels dataset to maintain ownership and tax information, record zoning and other planning designations, track annexations, maintain corporate boundaries and develop future land use plans. Additional datasets such as sanitary sewer infrastructure have been developed in the last five years and were created using survey-grade GPS and conventional surveying techniques. The data were used to develop engineering models, therefore high positional accuracy was necessary. Utility infrastructure, such as sanitary sewer, and its relationship to property boundaries is constantly under consideration by engineering and planning staff, which highlights the substantial difference in accuracy between the two datasets. All of Rapid City's standard base data layers, including parcels and orthophotography, are also published on a website for public use. Despite numerous disclaimers describing the appropriate and intended use of the data, there are those who remain bothered by the discrepancies in the parcels as they relate to the aerial imagery. Initially, the parcels were used mostly as a representation and the tabular information associated contained specifics about the land such as area, ownership and tax value.

1.1 History of Cadastral dataset of Rapid City

The original cadastral dataset maintained by the GIS Division was developed in 1989 (see Figure 2 for overview) from plats at three scales and adjusted to United States Geological Survey (USGS) 7.5 minute quadrangle section corners resulting in some errors. From 1989 through 2000, parcels were added by digitizing and using coordinate geometry input methods (COGO). Rectified but not orthto-corrected aerial images were used to help align the property lines. As new imagery was acquired, many lines had to be adjusted, especially in areas of high relief (Rapid City GIS Division 2009). In 2000, the parcels were converted to Environmental Systems Research Institute (ESRI)'s ArcInfo Coverage format, and again some errors were introduced. It was noted by GIS Division staff that "this conversion yielded reasonably good data in the eastern half of the county, but problems were noted in the western half" (Rapid City GIS Division 2009). Not only were conversion errors introduced, but sometime after the project was finished, it was also discovered that the conversion vendor incorrectly moved section lines in some tax parcels to match the digital line graph (DLG) section lines, rather than moving the parcels to the correct section and that water boundaries were erroneously incorporated to represent parcel boundaries. To date, these problems have not been corrected. In 2003, the ESRI ArcInfo parcel coverages were converted into one contiguous county-wide ArcSDE feature class. Maintenance of the parcels has continued using ESRI's ArcMap desktop software by COGO input and other editing techniques.

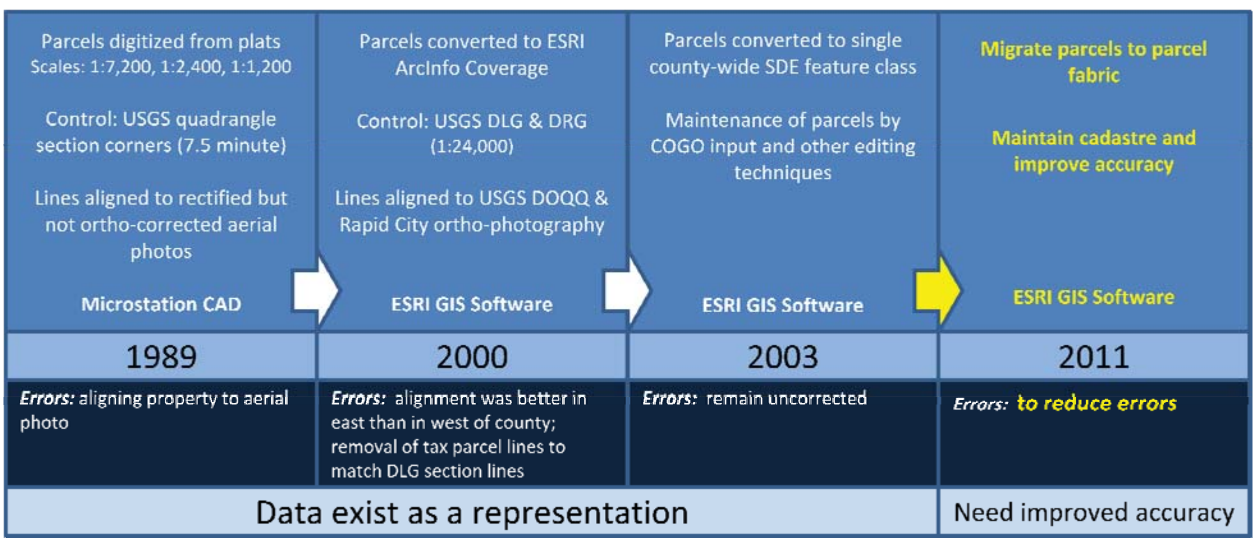


Figure 2. Summary of the Rapid City parcels dataset history.

From the original development of the parcels dataset, through the conversions discussed above, errors have been introduced and continue to be propagated. Even the current methods used for updating and maintaining the data introduce, if not maintain, error in the dataset. For example, when an area is newly subdivided, the surveyor of record's platted information is reproduced digitally using software with coordinate geometry (COGO) input capabilities. Data integrity is then often compromised so that the shape(s) can be fit into the area available in the parcel layer instead of being truly represented.

Rapid City's cadastre in its current state is representative of the condition of cadastral data managed by countless organizations around the world. As Elfick (2006a) points out, "Historically, cadastral layers in GIS systems did not have a critical need for survey accurate data, as the information in the databases was spatially 'pictorial'." This was acceptable at the time because cadastral data was being developed primarily by counties for taxation purposes and little if any other relevant spatial data existed. If other data layers were developed, they were simply referenced to the existing data in the database or 'rubber sheeted' to fit (Harper 2006).

One of the main factors that limited spatial accuracy in GIS systems was the capacity of hardware and software and their inability to handle geodetic coordinate systems effectively. However, as both of these have improved this is no longer a limitation. The wide availability and substantial improvements in spatial data quality provided by GPS, aerial photography and other data collection technologies have found the spatial management and improved accuracy of cadastral databases struggling to keep pace (Harper 2006).

1.2 Errors in spatial data

Errors are inherent in geospatial data. Goodchild (1992) explains that data collected by observation are almost always subject to error and that spatial data seem to suffer from imperfect quality more than other data. He also contends that this could be a result of data developed by subjective interpretation rather than precise measurement. Foote and Huebner (1995) further describe error as encompassing "both the imprecision of data and its inaccuracies." They explain that there are three main categories of error and list the errors involved in each. Figure 3 outlines this categorization. The items highlighted in yellow followed by specific descriptions apply to the dataset used in this study and illustrates that errors from each of the three categories are present in Rapid City's cadastre.

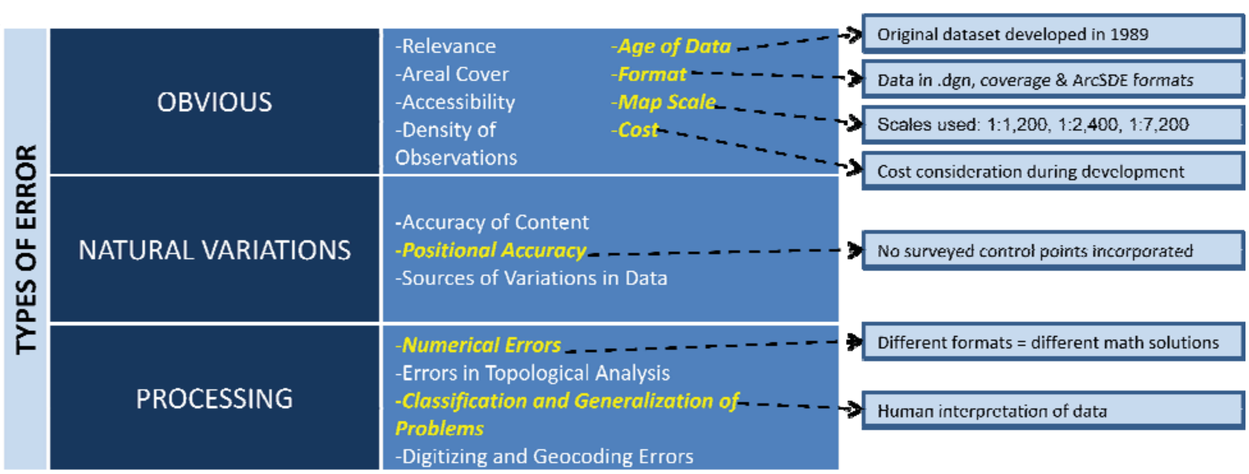


Figure 3. Sources of error commonly found in geospatial datasets as discussed by Foote and Huebner (1995) and how they apply to the dataset in this study.

Making changes to the parcels dataset, whether to accommodate the dynamic nature of land configuration or make adjustments to improve accuracy, currently poses a problem. Handling other land-dependent layers, such as zoning, future land use, street centerlines, corporate limits, annexation boundaries, and utility features becomes very resource-intensive if all changes being made to the land base are to be reflected in the associated layers. Historically, these changes have not been consistently maintained in the associated layers producing a less than visually appealing result when the parcels are overlain and troubling results when some spatial data analyses are performed.

Two layers in particular are driving the City's interest in improving its parcel base: zoning and future land use. Having these layers available and up-to-date would increase staff efficiency when reviewing development submittals, improve customer service by having the data accessible to the public and help expedite planning and engineering studies.

1.3 Parcel Fabric: what is it?

Rapid City has several cadastral objectives that are shared by many and include the development of cadastral layers with higher spatial accuracy, applying cadastral adjustments to associated layers (Figure 4), increasing accuracy of the fabric over time by continuous updating and maintenance and storing legacy data within the cadastre fabrics (Bhowmick et al. 2008). Environmental Systems Research Institute's (ESRI) parcel fabric data model appears to meet these objectives.

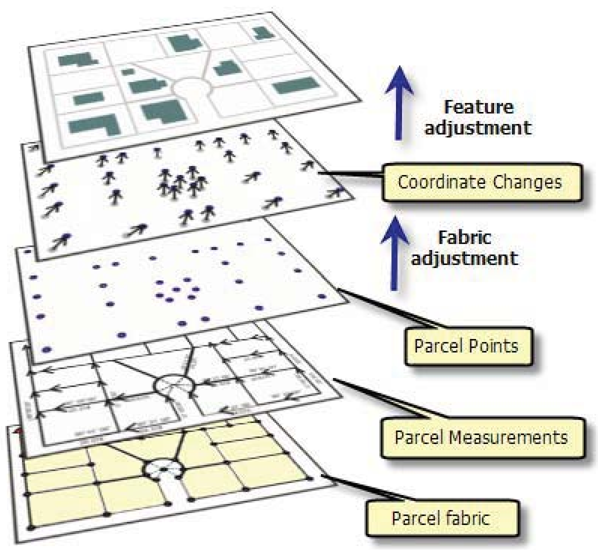


Figure 4. A representation of ESRI's parcel fabric and how it interacts with associated layers (ESRI 2011).

ESRI's cadastral solutions, including the parcel fabric data model, have been in development for quite some time and are the result of multiple collaborations. The data model was crafted to consider the objectives of the Cadastre 2014 Vision set forth by the International Federation of Surveyors (FIG) Commission 7 group and the Federal Geographic Data Committee's (FGDC) Cadastral Data Content Standard for the National Spatial Data Infrastructure (Kaufmann & Steudler, 1998; ESRI & Kaufmann, 2004). Figure 5 is a generalized timeline of the introduction of cadastral standards, collaborations and products leading up to the integration of the parcel fabric data model in ESRI's current software core.

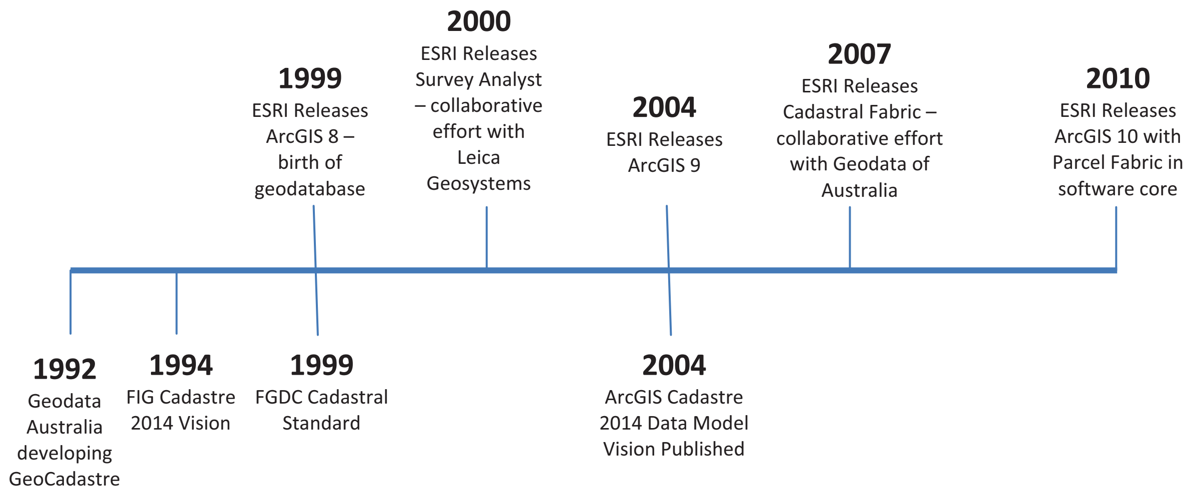


Figure 5. Generalized timeline of the introduction of cadastral standards, collaborations and products leading up to the integration of the parcel fabric data model in ESRI's software core.

The parcel fabric, recently introduced by ESRI in 2010 and the focus of this project, is the result of over two decades of research and development by ESRI and its partners. The parcel fabric as it is known today was based on a process developed by Geodata of Australia called GeoCadastre (Geodata 2006). This process included migrating a parcel network fabric into the GIS database and then allowing an adjustment and update of survey points and features within the GIS while retaining original survey title data. For ESRI, this was a new data model and concept for storing parcels and took "several years of joint product development as ESRI had to incorporate cadastral storage in the geodatabase as defined by points and lines (survey methodology) rather than shape files (GIS/mapping methodology)" (Geodata 2006).

Careful consideration given to national and international standards, decades of development and the successful implementation of the GeoCadastre process in other countries (e.g. South Africa (Elfick & Hodson, 2006); Australia, New Zealand (GeoData, 2010); Vietnam (Huong, 2010); USA (i.e. Florida: (Capobianco & Mann 2009); Denver: (Genzer & Tessar, 2011)); (see Konecny, 2011 for overview of variation in land management systems in diverse geographic regions) signifies that a potentially stable, comprehensive solution has been developed. ESRI committing to this model and incorporating this package into the standard GIS software provides further confidence that this is a model/framework that was developed with longevity in mind. Existing cadastral information can be imported into the parcel fabric which "is a topologically integrated geodatabase dataset designed to store both a continuous parcel fabric that covers a jurisdiction as well as survey-based subdivision plans without loss of any information in the original survey record" (ESRI UK). The dataset resides inside a geodatabase under a feature dataset and an internal topology composed of a complex network of points, line and polygons is used to maintain and improve this data (ESRI 2010) (Figure 6).

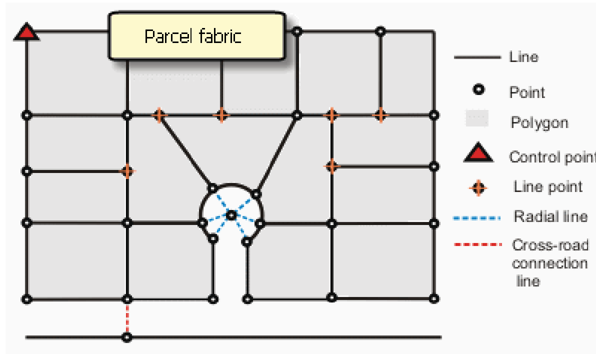


Figure 6. Diagram of the components making up ESRI's parcel fabric dataset (ESRI 2010).

The ability to import existing data and improve it over time is very important to the City of Rapid City from a feasibility standpoint. Some have alluded that existing datasets should not be salvaged and continued to be improved upon, but rather the fabric should be built from scratch to ensure its integrity (Harper & Lee 2008). For a GIS Division with a full-time staff of three supporting both county and city GIS activities, it is simply not reasonable to use this approach.

The parcel fabric functions by fitting parcels into their appropriate location in the fabric, based on points the parcel has in common with the fabric (see Figure 4). This is done by using a joining procedure, surveyed control points and a least squares adjustment (see Appendix A or methods section for further information) to minimize the amount of warping that occurs (ESRI 2010). The program also allows a rank to be placed on lines that make up the parcels in the fabric so as better data is acquired, the objects ranked the highest take precedent and the parcels update accordingly. Another feature that this tool introduces is the ability of other feature classes to be associated with the parcel fabric. This provides an opportunity for associated layers that are cadastrally dependent to be updated anytime the parcel boundaries change and therefore reduce discrepancies, such as mismatching of boundaries, as currently exists. A couple of other features of interest include the preservation of historical data and the ability to use multiple projections. As land is subdivided or re-configured, the parcel fabric maintains records of previous transactions enabling the user to review the state of a chosen area over time. The parcel fabric can also reside in a geographic datum and can be edited in any projected coordinate system that uses it. This provides organizations maintaining data across many projection zones the opportunity to have all parcels in one parcel fabric and edit the parcels in their respective projected coordinate systems.

1.4 Importance of land management

The interest that the City of Rapid City is illustrating in improving their parcel base seems to be paralleling a national, as well as global movement with historical roots. The establishment of property cadastres and land registration systems can be traced back to the 14^{th} century BC in Egypt and was driven by taxation (Southern Illinois University Carbondale 2010). More recently, the United States of America (USA) found it necessary to develop a system for dividing up the nation's land. This was initiated by the government's need to raise money, and land was an available resource. The Land Ordinance of 1785 encouraged land development activities when it gave Congress the power to raise money by direct taxation (Binge 2010). Early cadastral systems served the purpose of tracking the location and extent of landholdings and associated ownership and rights, and have been implemented by land surveyors for over 200 years. However, they lacked absolute accuracy because the surveys were not referenced to a geodetic control system (Konecny 2011).

Land records as they exist today in the USA are administered by local governments and have historically operated on a grantor/grantee-based system rather than a parcel system (Foster 2008). As a result, there is a huge variance in the way local land systems are funded, constructed and managed. All 50 states have different codified laws governing the title and ownership of real property (Binge 2010). This is one of the primary reasons why the USA does not have a national cadastre; a fact that is surprising to many because of the real estate and technical wealth of the country.

Experts have been making the case for over 50 years that the USA needs a nationwide cadastre. In 1980, the National Research Council (NRC) released a report outlining the need for a national cadastre along with recommendations for implementing policies and procedures in support of it (Palatiello 2008). Thirty years have since gone by and a nationwide cadastre is still not in place. However, as the country's population and parcel densities increase, there is a greater sense of urgency to develop contiguous parcel coverage. Management of public infrastructure, response to natural disasters and homeland security are all dependent on parcel-level information. American consumers pay high property transaction fees because of the complexity of finding property information, and some have even argued that a nationwide cadastre could have provided an early warning system to the mortgage crisis (Palatiello 2008).

As is evidenced by the amount of time that has gone by without a national parcel cadastre being developed, Binge (2010) contends that "the financial and technical issues are minor compared to the organizational and political ones. With thousands of counties and other jurisdictions producing and maintaining cadastral records, significant challenges exist politically and physically in developing and maintaining cadastral coverages that span across county and state boundaries."

Although political and organizational hurdles are largely responsible for the delay in a national cadastre, technical capability has been a limitation in building widespread, accurate cadastral datasets. Cadastral layers in geographic information systems (GIS) have until recently been driven by activities such as cartography and tax assessments (Eflick & Hodson 2006). This resulted in map products that were graphical representations rather than spatially accurate, which created quite a separation between land surveyors and GIS professionals. Technology has now advanced to a point that new methodologies supporting cadastral record maintenance have been introduced and include the ability to maintain spatial accuracy across all layers. This seems to be helping to bridge the gap between the two professions which is a positive sign because they are so complimentary. As Eflick and Hodson (2006) point out "the traditional parcel base-map is evolving into a cadastral fabric layer for supporting spatial coordinate quality." Jones (2010) argues that technological advances and a movement towards a national cadastral dataset create an opportunity for surveyors to regain a leadership role in geospatial technology "by looking at their data as a societal resource rather than a proprietary asset for creating and interpreting boundary information."

Rapid City's parcels dataset, which has been used largely as a representation, has served its original purpose. However, with the advancement of spatial data technologies and an increasing integration of digital data systems into daily workflows, the City and its stakeholders have expressed a desire to improve the accuracy of the parcels dataset and related base data layers. The remainder of this paper will outline and evaluate a workflow for preparing and importing existing data into the parcel fabric, adjusting the parcels to control points and performing an accuracy assessment of the adjustment, and applying the adjustments to an associated layer.

2 Methods

2.1 Data

The data to be used for this study is a small portion of parcels from Rapid City's existing cadastre. The area was chosen because a major arterial street reconstruction project was recently completed in the area (Figure 7) providing an ideal comparison dataset for use in this study. During the design phase of this street project, an accurate property layer had to be assembled so properties impacted by construction activities could be identified. Detailed property information was also necessary for developing construction easement documents and acquiring necessary rights-of-way. To develop the property layer, property corners in the project area were located and recorded using a mix of GPS and conventional surveying methods. Plats, easements, deeds and other existing property documentation were retrieved from the county courthouse. A cadastral layer for the project area was then constructed in AutoCAD Civil 3D 2011 using the plats and surveyed property corner information. For this parcel fabric study, the surveyed property corners provided geodetic coordinates for import into the fabric to adjust the existing parcels to. And, having the independently created cadastral layer provided an opportunity for a comparison to see how well the parcel fabric adjusted the parcels in the test area.

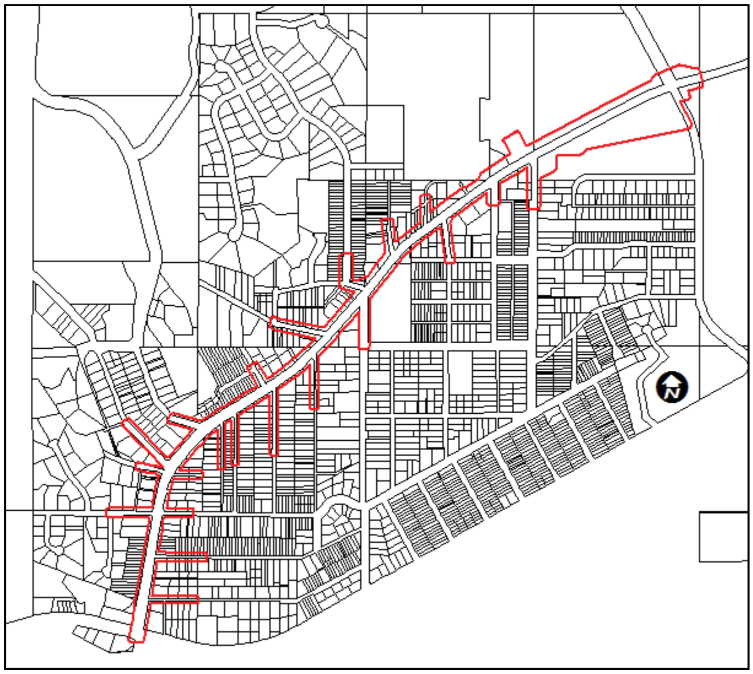


Figure 7. Map illustrating the cadastral data layer that will be used for the purpose of this study. This is the Canyon Lake Drive neighborhood area and contains approximately 675 parcels. The red line delineates the street reconstruction project zone and Canyon Lake Drive.

2.2 Workflow

Five steps identifying the workflow necessary to test and implement the parcel fabric for Rapid City have been identified and are summarized in Table 1.

Table 1. Five steps outlining the flow of work performed in this study.

STEP 1	Building Framework
STEP 2	Preparing and Loading Data
STEP 3	Parcel Adjustment
STEP 4	Accuracy Assessment
STEP 5	Adjustment of Associated Layer

2.2.1 Step1: Building the data migration framework

The first step in the workflow development of this project was reviewing existing documentation to identify the necessary steps required to prepare the data for loading into the parcel fabric. This included reviewing ESRI documentation and other available literature (which is limited since this is still a relatively new component) as well as conversing with ESRI personnel. The workflow step developed consisted of approximately twelve items. This includes technical and data-related tasks such as verifying software version, installing necessary components such as the *Curves and Lines* tool, creating workspaces and verifying projection and coordinate system information. Feedback in the form of verbal communication was received and incorporated into the final workflow procedure.

2.2.2 Step 2: Preparing and loading data to the parcel fabric

The second step developed was preparing and loading existing data into the parcel fabric and documenting the steps involved. This is perhaps the most important step in the process. If the existing data cannot be successfully loaded to the parcel fabric, none of the other project objectives can be met.

An extensive amount of documentation research and numerous interactions with ESRI's Land Records Division were necessary to successfully develop a workflow item for this step. Rapid City manages both platted lots and tax parcels in its cadastre, so two different types of parcel data had to be considered when developing the workflow item. Rapid City currently performs its parcel maintenance on the lot lines layer and dissolves by attributes to derive tax parcel polygons.

As a result, the lot lines layer was the first layer to be prepared for loading. Because the parcel loader requires a topology in order to load data to the parcel fabric, the first attempt at developing the process was to create lot polygons from the lot lines and then creating and verifying a topology that they participated in. Attributes, such as parcel identification number (PIN) and parcel type were populated to maintain feature identity upon loading. Using the six topology rules required by the parcel fabric loader (Table 2), the topology that was created was verified successfully. However, the parcel loader failed to load the lots citing topology errors. Further investigation revealed that even though the data passed all of the topology requirements, additional editing of the data was necessary before it could be loaded into the fabric. For example, lines needed to be planarized, or broken at intersections, (Figure 8).

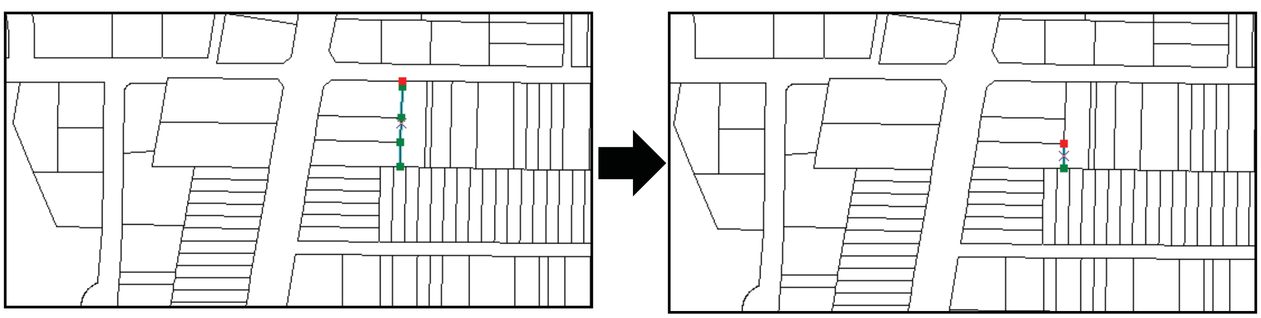


Figure 8. Line prior to (left) and after (right) planarizing.

After the planarizing of the lines was completed, a second process was run using a developer sample tool, called *Curves and Lines*. This tool was used for splitting "multi-segment lines at inflection points; for example, at locations where one curve transitions into another, or at sharp bends or corners between two straight-line segments (ESRI 2010)." The option is also available to convert densified lines into two-point parametric curves (Figure 9) by fitting circular arcs to the straight-line segment sequences. This option was not executed on the sample data because densified lines can also be converted to curves when the data is loaded to the parcel fabric via the parcel loader (ESRI 2011a).

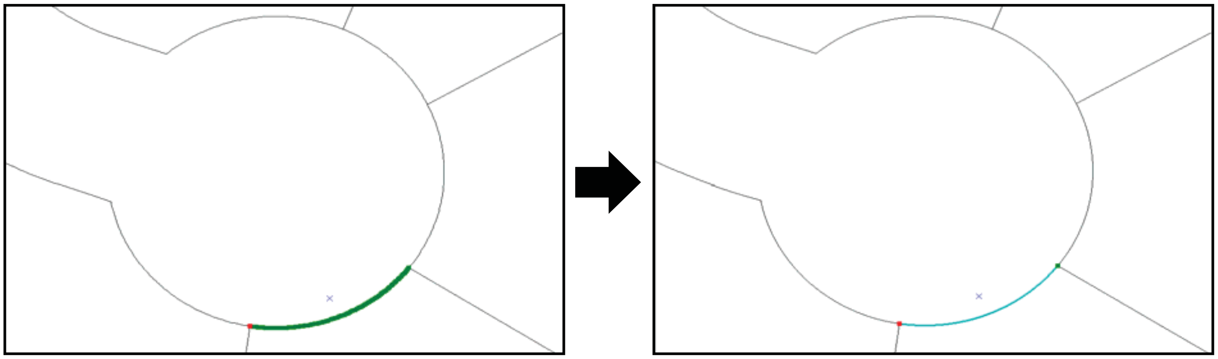


Figure 9. Densified lines delineating curve (left) and two-point parametric curve (right).

The lots were successfully loaded to the parcel fabric, but completing this step was challenging because the dataset met the required topology rules (Table 2), prior to the additional processing.

Table 2. Topology rules required by the parcel loader to load data to the fabric.

1.	LINES	Must Not Self-Overlap
2.	LINES	Must Not Self-Intersect
3.	LINES	Must Not Intersect or Touch Interior
4.	LINES	Must Be Covered by Boundary Of
5.	POLYGONS	Boundary Must be Covered By
6.	LINES	Must be Single Part

Because the parcel fabric can manage different types of parcels (e.g. lots, tax parcels, easements, etc.) the next dataset to be loaded to the fabric was the tax parcels. Assuming that the same approach the City had been using for deriving tax parcels (dissolving by attribute) would be appropriate, tax parcels were derived from the lot lines that had been successfully loaded to the fabric. Again, a topology was created and verified and the tax parcels were loaded. They were within the tolerances required by the parcel loader and loaded without error. However, upon close visual inspection, the tax parcel lines were not coincident with the lot lines loaded previously. Apparently, the process of dissolving the features by attribute resulted in a slight amount of movement. The concern with the movement is mostly cosmetic in nature, since it did meet the tolerances required by the parcel fabric. However, Rapid City did choose to pursue another option that would result in coincident lines.

To address this issue, tax parcels were re-created from the lot lines. Two different approaches can be used to isolate the lot lines that need to be removed in order to derive the tax parcels. The first option is to simply order the layers in the *Table of Contents* of the project so that the tax parcels are on top of the lot lines and visually select all of the lot lines that aren't parcel boundaries and delete them. The other option, and one that will be more practical for Rapid City to use on the county-wide dataset, is to use select by location with *Target layer(s) features are within (Clementini) the Source layer feature* option selected. This should result in most of the lot lines that are not tax parcel boundaries being selected and they can all be deleted at the same time. However, if this method is used, it is important to check and make sure no lines were selected and deleted that should not have been. This can be done by ordering the layers in the *Table of Contents* such that the lot lines are on top and the tax parcels are beneath. Then by visual inspection it can be seen if any were deleted that shouldn't have been. Another way to find out if any lines were erroneously removed is by converting the lot lines to polygons and comparing the count to the original tax parcel layer.

The tax parcel lines and polygons were again successfully loaded to the fabric and checks were performed to ensure that all of the features loaded successfully. Comparing feature counts against the original layers and querying for zero geometry objects were few of the many checks performed.

Following the parcels, the control points were loaded to the fabric. Associations were made between the parcel corners and corresponding control points (see step 3 for more detail) (Figure 10).

Figure 10. Control points loaded into the fabric for the study area and associated with the appropriate parcel corners.

Control points define accurate, surveyed x,y,z coordinates for physical features on the surface of the earth, and in this study consisted of property corner monuments that had been located on the ground and coordinates recorded. A control point network is added to the parcel fabric so that parcels can be adjusted to the control point network in a fabric least-squares adjustment, resulting in accurately georeferenced parcels (see step 3 for more details). While parcel dimensions accurately define parcel boundaries in relation to each other, control points, when used in a least-squares adjustment, result in accurately defined spatial locations for parcel corner points (ESRI 2011).

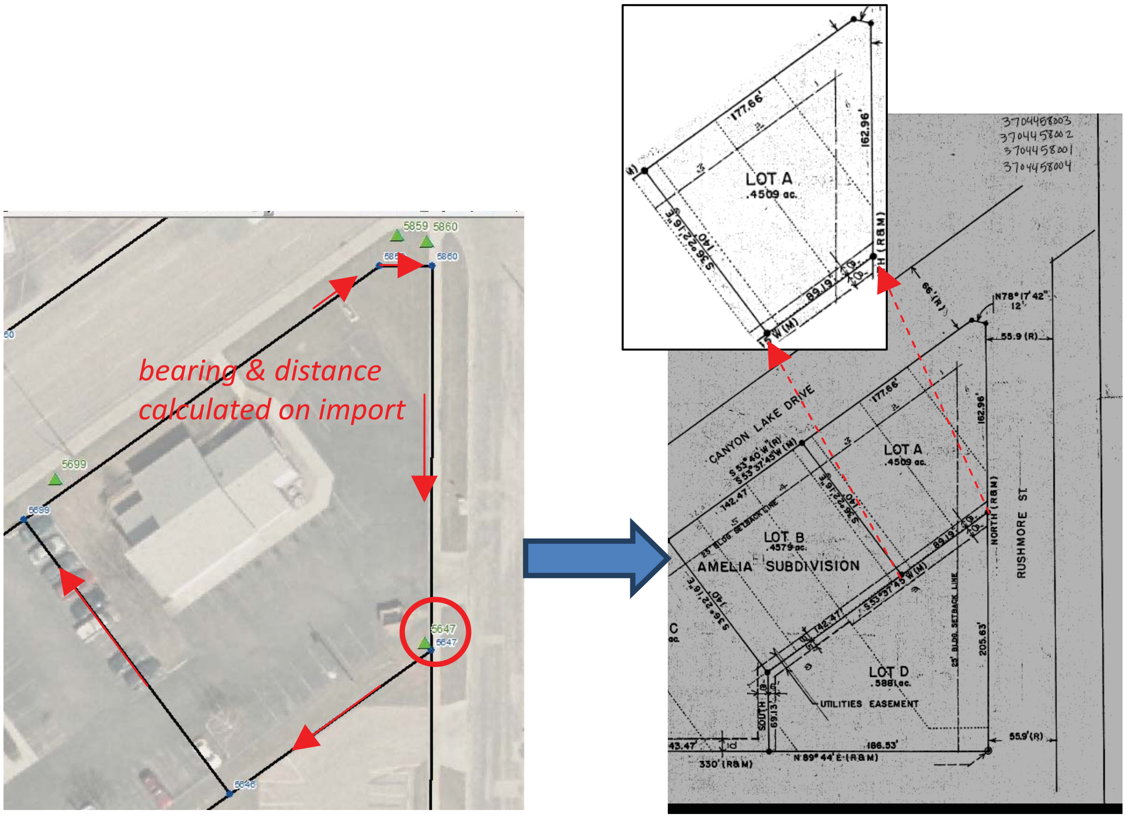


Figure 11. A parcel in the parcel fabric resulting from the import of existing data (left) and an image of its corresponding plat (right).

To summarize step 2: the existing parcels dataset consisted of parcel shapes without any coordinate geometry (COGO) attributes (i.e. bearing and distance of record) and did not necessarily truly represent the shape of the parcel (too many vertices and line segments making up the curves), was processed and imported into the parcel fabric. The data processing component of this workflow step consisted of breaking these shapes down into components that closely represent the platted shapes (Figure 11) (i.e. 2-point lines, and parametric curves) and was accomplished through planarizing the lines and identifying the curves. The result was a fabric-ready set of lines, points and polygons. The more closely each parcel represents its originally platted course, less editing and maintenance will likely be required once the data has been loaded to the parcel fabric (Denver GIS, 2011).

2.2.3 Step 3: Adjusting parcels to control points

As previously mentioned, the third step in the process is to use the least-squares adjustment built into the parcel fabric to adjust the existing parcels to surveyed control points. During this process control point coordinate values are held fixed while the horizontal and vertical coordinate system of the control points is transferred to the parcel fabric. In other words, control points are processed together with recorded dimensions to derive new, more accurate coordinates for parcel corners (ESRI 2011). Line dimensions (attributes representing the original survey) are not changed, but fabric point coordinates are updated and the geometric and spatial representation or the parcel line shape is updated. The result is an accurate coordinate-based cadastral system.

Least-squares adjustments are one of the most rigorous yet easy to apply without bias adjustments and are defined by Craig & Wahl (2003), as being "based on the mathematical theory of probability and the condition that the sum of the squares of the errors times their respective weights is minimized." They also point out that one of the most important benefits of using the least-squares method of adjusting is that all types of survey measurements can be analyzed simultaneously.

In the parcel fabric, this adjustment is applied to a group of selected parcels and should be in an area that has a reasonably well-balanced geometric shape with redundant measurements and evenly distributed control (Figure 12).

Figure 12. An example of an area of parcels that is well-balanced geometrically with evenly distributed control.

Redundant measurements are multiple observations made of the same point, as shown in Figure 13, to determine its coordinates.

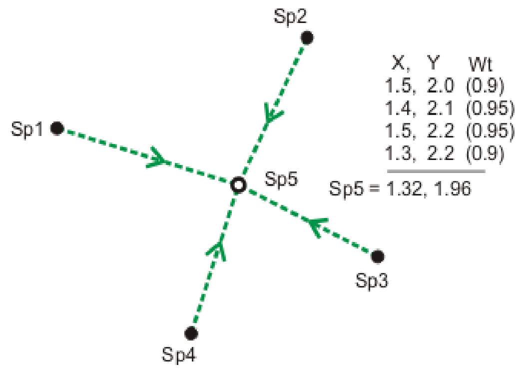


Figure 13. An example of redundant measurements (ESRI 2011).

Repeated observations validate a measurement network and a parcel fabric is a redundant measurement network. As pointed out by Craig & Wahl (2003), "Prudent surveyors check the magnitude of the error of their work by making redundant measurements."

Each parcel dimension and thus each parcel in the parcel fabric can have an associated accuracy. This is because parcel dimensions are derived from raw survey measurements which have associated accuracies. By default, accuracy in the parcel fabric is defined by survey date because in general, surveying equipment is more precise today than it was in the past (ESRI 2011).

Accuracy assignments in the parcel fabric are important in the least-squares adjustment because parcels with a higher accuracy assigned to them will have a higher weight in the adjustment and will adjust less than those parcels with lower accuracies. In other words, low-accuracy parcels will adjust around the more accurate parcels (ESRI 2011). ESRI uses seven accuracy levels with the highest level of accuracy given to the most recent surveyed data, mainly because of the ability to collect more precise data with modern surveying equipment, as shown in Table 3.

Table 3. Breakdown of the accuracy categories used in the parcel fabric (ESRI 2011). This is based on the age of the data.

Accuracy level	Std. deviation bearing (secs)	Std. deviation distance (m/ft)	PPM (m) (parts per million)	Description
1	5	0.001/0.00328	5	Highest
2	30	0.01/0.0328	25	After 1980
3	60	0.02/0.0656	50	1908–1980
4	120	0.05/0.164	125	1881–1907
5	300	0.2/0.656	125	Before 1881
6	3,600	1/3.28	1,000	1800
7	6,000	10/32.8	5,000	Lowest—excluded from adjustment

Data that were imported in previous steps of the workflow were automatically assigned an accuracy level of 6, the lowest that can participate in an adjustment since the dimensions were calculated upon import and not entered from a plat. If the data had been entered off of a plat, then an accuracy level could have been assigned based on the date of the plat and would have ranged in accuracy between 5 ppm and 1,000 ppm.

Prior to running a least-squares adjustment, ESRI recommends checking the fit of control points. This calculates the transformation between the linked fabric point coordinates and the coordinates of the control points. The calculated parameters are then applied to the linked fabric point coordinates to compute temporary new values for the fabric point coordinates. The difference between the newly calculated fabric point values and the original control point values are reported as residuals for each active control point. Large residual values can indicate a problem in the data and should be investigated further. For instance, a large discrepancy (identified as being outside of the range of the rest) may be the result of a poor control point, inaccuracy in the parcel data or control points incorrectly matched to corresponding parcel points and should be further investigated prior to applying the adjustment.

Perhaps one of the biggest drawbacks of the least-squares adjustment is that one wrong piece of information can greatly distort the results of the adjustment. This is because in the squaring process large residuals are dominant. One major error ten-times larger than the others will have the same effect on the sum of the squares as will 100 of the others (Craig & Wahl, 2003). Therefore, it is imperative that the statistics be reviewed and suspect residual values addressed prior to committing an adjustment.

2.2.4 Step 4: Accuracy assessment

The fourth step in the workflow is to perform an accuracy assessment of the adjusted data. In this case, an AutoCAD layer that was independently constructed from original plat documents and surveyed control points was used to make comparisons. Plotting the parcel fabric with the AutoCAD layer and visually inspecting how the two overlap was the first assessment of how well the adjustment performed. In areas where there is no independent work to check against, a visual inspection against aerial photography or other such imagery will provide some verification of the success of the adjustment. However, visual inspection of the data is a qualitative assessment; therefore a more quantitative approach was also used. To do this 12 samples were taken and ranged from seven to 44 parcels in size. Each sample was adjusted using the least-squares method described above. Accuracy of fit was performed visually by viewing how well the parcel boundaries overlapped as well as quantitatively by analyzing the output statistics provided by the software and ranked (see Table 5) based on what percentage of the parcel lines were within +/- 2 ft of the control layer boundaries. The percentage of parcel lines within +/- 2 ft of the control layer was determined by buffering the control layer lines and using the *Select by Location* feature in the software.

Standards, such as the United States Geological Survey's (USGS) National Map Accuracy Standards (NMAS), were reviewed when considering an appropriate tolerance for evaluating the accuracy of parcel fabric adjustments. The NMAS states that "for maps on publication scales larger than 1:20,000, not more than 10 percent of the points tested shall be in error by more than 1/30 inch, measured on the publication scale; for maps on publication scales of 1:20,000 or smaller, 1/50 inch." (USGS 1947) A standard publication scale for cadastral mapping is in the 1:1000 – 1:1200 range (FIG 2009; and Kennedy & Ritchie 1982) translating to an accuracy of 90% of all measureable points / lines falling within +/- 3 ft to +/- 3.33 ft (Foote & Huebner 1995) and tested by comparing to corresponding positions as determined by surveys of higher accuracy (USGS 1947). However, as pointed out by the International Association of Assessing Officers (IAAO) "The NMAS is most appropriate for paper maps which are only viewed at a printed scale," and also contends that "no one accuracy standard meets all needs" due to the differences between urban and rural environments (IAAO 2009).

For this study, it was understood that the cadastral data will not be published at a static scale, the area under consideration is urban in nature, and Rapid City has obtained highly-accurate utility location information which is helping drive the desire to improve related cadastral information. Knowing this, an accuracy range of +/- 2 ft was selected for evaluating parcel fabric adjustments for this project and was based partially on tolerances that were established by a parcel fabric project implemented by a utility company (Colorado Springs Utilities) and whose cadastral products are also consumed by local government agencies (Moran, et al. 2008). In summary, for the purpose of this study, accuracy was assessed using the ranking system summarized in Table 4.

Table 4. Summary of ranking system used to evaluate success of least-squares adjustment.

Rank	Percentage of Parcel Lines +/- 2.0 feet From Control Layer
1	100 – 90%
2	89 – 75%
3	74 – 50%
4	49 – 0%

An initial assessment of the 12 samples found that only 8.33% of the samples were fitting well (ranked a 1 or 2) prior to any adjustments being applied. After the first adjustment was performed, this only increased to 25% of the samples (Table 5).

Table 5. Percentages of lines in each sample that were within +/- 2 ft of the control layer.

Sample	% Match pre-adjust	Rank	% Match after 1st adjust	Rank
1	11.76	4	64.71	3
2	15.79	4	60.53	3
3	5.00	4	21.67	4
4	25.00	4	83.33	2
5	10.53	4	63.16	3
6	9.52	4	47.62	4
7	73.17	3	82.93	2
8	0.00	4	70.59	3
9	95.35	1	93.02	1
10	10.26	4	61.54	3
11	26.83	4	80.49	2
12	14.81	4	55.56	3

The reasons for this may be the result of a number of problems that include:

(a) incorrect shape of the parcel boundaries
(b) inaccurate control points
(c) inadequate control points
(d) disproportionately distributed control points (i.e. larger number of control points on the perimeter of the sample and/or clustering of control points with large gaps between control points

(a) **incorrect shape of the parcel**: If the shape of the parcel is incorrect, then the shape will need to be re-created using the original plat document and re-joined to the fabric. Obviously knowing this is difficult without a dataset to compare to, as has been done during this study. When the northing and easting values are not converging to zero or stabilizing during the adjustment can be indicators of incorrect shape. Therefore, visual inspection against a control layer (as was done in this study) or aerial imagery can be used.

(b) **inaccurate control points**: If a control point is problematic then it will need to be either corrected or de-activated and the adjustment re-applied. High or irregular residuals during the check fit are an indicator of an inaccurate or incorrectly associated control point. Visual inspection of the point locations against aerial imagery can be used to verify the location of the point.

(c) **inadequate control points:** There may be instances where there are few if any control points in an area that correction is desired. If there are none, obviously some will need to be acquired. If there are too few to perform the adjustment, or the points available are clustered, some additional points should be obtained to strengthen the adjustment.

(d) **distribution of control points**: For cases where the distribution of control points is poor additional control points will need to be added before applying an adjustment. Distribution of control points causing an adjustment to perform poorly can be identified by ruling out problems addressed in points (a) and (b) above. If neither control point accuracy nor shape appears to be an issue, then distribution of control points should be evaluated. If there are more control points around the outer edge of an adjustment area than inside, and the adjustment performed well around the outer boundary but not well internally, then it is reasonable to pursue adding some additional control points inside the adjustment area.

To identify what issues might be inhibiting the potential of the parcel fabric adjustments, each sample area was evaluated starting with the lowest ranking sample. Going through each of the steps listed above, a visual inspection was performed comparing the parcel shapes in the sample area to the control layer, assessing the reasonableness of the control point accuracy and looking at the number and distribution of the control points. Notes were taken regarding what was observed and appropriate action taken (e.g. adding additional control points, inactivating bad control points, improving distribution of control points by adding more, etc.). In areas where the distribution of control points was obviously skewed (e.g. all control points located around the outer edges), an attempt was made to disperse the added points in as balanced of a manner as possible.

2.2.5 Step 5: Adjusting an associated layer: zoning

The fifth step in the workflow process is to apply the parcel adjustment to an associated layer. For this study, the zoning layer was chosen. If the desire is to adjust a parcel-based layer, such as zoning, it must be associated to the parcel layer being adjusted before the adjustments are performed. As such, the first step of this workflow was to verify that the zoning layer was associated with the parcels. After the parcels were adjusted, the adjustment vectors were then applied to the zoning layer resulting in the zoning layer now aligning with the parcels that were adjusted (sample 7) and thus moved during this process (Figure 14). Seeing this happen successfully was a big victory because one of the biggest challenges the City faced adjusting parcels in the past was how to efficiently and accurately apply these improvements to related layers.

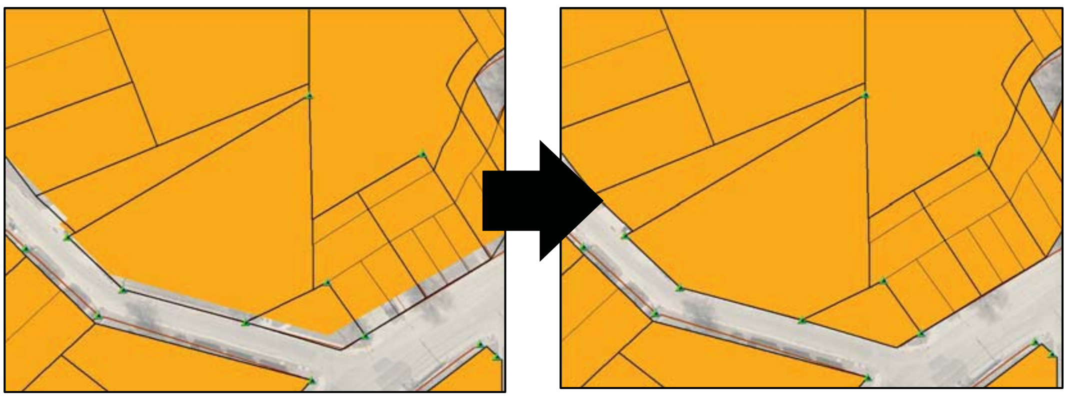


Figure 14. Zoning (shown in orange) prior to (left) and after (right) the parcel adjustment vectors were applied.

3 Results

The development of the workflow described in this paper has been an interactive and iterative process with Rapid City to ensure that the process can be executed successfully and applied to the remaining parcels for Rapid City and Pennington County (approximately 40,000 parcels). At the conclusion of each step a written workflow process has been provided. All workflow steps have been tested by at least one staff member of the GIS Division for usability and feedback has been incorporated back into the final workflow. A survey was provided and results compiled documenting the usability of the final workflow that was developed (Appendix C).

While performing the adjustments of the cadastre during this study the previously known errors inherent in the cadastre dataset (see Section 1.1) were confirmed. These errors were found to be randomly distributed throughout the dataset. For example, the parcels were not shifted consistently in any one direction or by a consistent amount of distance. Because the error is random throughout the data, it was found that errors were minimized during the parcel adjustment step in this study, when control points were evenly-distributed. The least-squares adjustment method utilized by ESRI's parcel fabric was found to work well in fitting the data. This was evidenced by the improvement seen in the percentage of parcel lines falling within +/- 2 ft of the control layer. The reason that this method works well is due to its ability to analyze different pieces of data (e.g. angles, distances and control coordinates) simultaneously. Although this method is a very robust mechanism for adjusting data, it can also quickly propagate errors in the parcel fabric. This is because in the squaring process of a least-squares adjustment, large residuals play a dominant role (Craig 2003). Therefore, as previously mentioned, it is important to check the results at each step of the proposed workflow and perform accuracy assessments when applicable. This should especially be done prior to committing to adjustments to eliminate erroneous data.

Accuracy of the parcels was greatly improved using a multi-step reiterative adjustment procedure as outlined in the methodology. During this study two adjustments were required to reduce inaccuracies and are summarized in Table 6 below.

When the data was first loaded into the parcel fabric (step 2) and compared with the Autocad layer only one sample, (8.33%) was ranked 1 (i.e. containing > 90% of the parcel lines within +/- 2 ft of the lines in the control layer (Table 6)) and ten samples (83%) ranked 4 (i.e. <50% of the parcel lines being within +/- 2ft of the control layer lines (Table 6)). After applying the least-squares adjustment (see 1st adjustment, Table 6) the number of parcel lines that were within +/- 2ft was somewhat improved. The number of parcels ranked 4 reduced from 83% to 16%, 50% of the samples were ranked 3 and 25% ranked 2 (Table 6). After evaluating each sample for adjustment performance and addressing any deficiencies or inaccuracies (see Table 7), a second adjustment was applied resulting in 75% (9 out of 12 samples) achieving greater than 75% of the parcel lines falling within +/- 2ft of the control layer lines.

Table 6. Summary of the quality of the parcels prior to applying any adjustment, after the first adjustment was applied and again after revisions were made for each sample and a 2nd adjustment was applied.

Sample	% Match pre-adjust	Rank	% Match after 1st adjust	Rank	% Match after 2nd adjust	Rank
1	11.76	4	64.71	3	94.11	1
2	15.79	4	60.53	3	81.58	2
3	5.00	4	21.67	4	23.33	4
4	25.00	4	83.33	2	97.22	1
5	10.53	4	63.16	3	94.73	1
6	9.52	4	47.62	4	68.25	3
7	73.17	3	82.93	2	82.93	2
8	0.00	4	70.59	3	94.11	1
9	95.35	1	93.02	1	93.02	1
10	10.26	4	61.54	3	66.67	3
11	26.83	4	80.49	2	82.93	2
12	14.81	4	55.56	3	85.19	2

Of the 12 samples that were adjusted, one sample (No 3) showed no improvement, four samples (1, 4, 5 and 8)) improved from rank 4 to rank 1 (> 90% of lines within +/- 2 ft); two samples improved marginally (rank 4 to 3 (50 – 74% of lines within 2ft)) and the remaining samples improved to within 75% - 89% of lines within +/- 2ft. The reasons for these improvements and lack of improvement (e.g. sample 3) are summarized in Table 7. Overall improvements were possible by adding between one and six control points.

Table 7. Assessment of problems associated with parcel accuracy for each sample and is based on the potential reason (a) incorrect shape of the parcel boundary (b) inaccurate control points, (c) inadequate control points and/or (d) disproportionately distributed control points (see step 4, Accuracy Assessment for further details).

Sample	**Problem of Accuracy**	**Fix**
1	inadequate control (c)	points added: 4
2	disproportionate control (d), inadequate control (c)	points added: 3
3	bad parcel shapes (a)	needs to be redigitized from plat.
4	disproportionate control (d), inadequate control (c)	points added: 6
5	disproportionate control (d), inadequate control (c)	points added: 3
6	disproportionate control (d), inadequate control (c)	points added: 5
7	disproportionate control (d), inadequate control (c)	points added: 1
8	disproportionate control (d), inadequate control (c), bad control (b)	points deactivated: 1 points added: 2
9	no problem	
10	disproportionate control (d), inadequate control (c)	points added: 6
11	disproportionate control (d), inadequate control (c)	points added: 6
12	disproportionate control (d), inadequate control (c)	points added: 5

The lowest ranking area, sample 3, (Figure 15 and Table 8), is the result of a bad shape. This is evidenced by comparing the parcels to the control layer, the adjustment solution not converging to zero and by the high maximum northing shift in the adjustment statistics. To improve this area, the parcels should be re-input from the original plats, joined to the fabric and re-adjusted. No matter how many times a least-squares adjustment is performed, if the shape being adjusted is not at least representative of the space available, it will never reach and ideal solution.

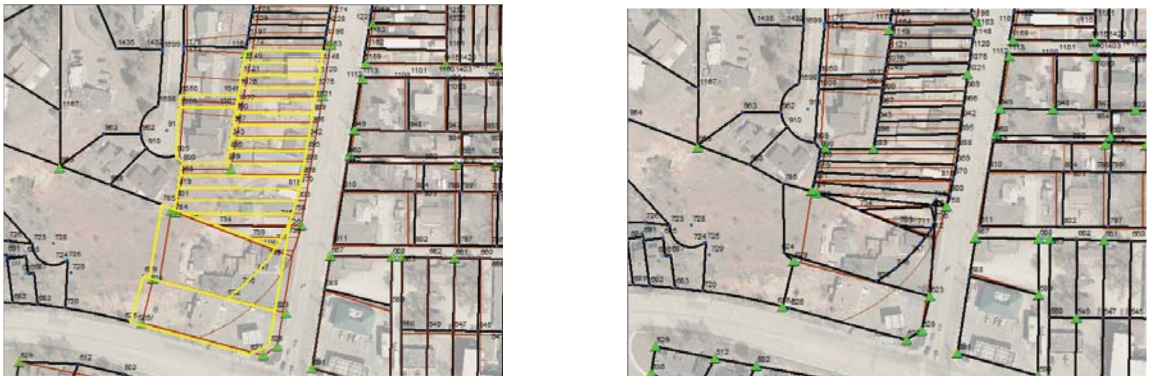


Figure 15. Sample 3 before adjustment was applied (left) and sample 3 after adjustment was applied (right).

Table 8. Sample 3 adjustment statistics.

Sample	**3 - (2)**
# Control Points	10
# Parcels	26
# Points	54
# Bearings	176
# Distances	176
#Unknowns	114
Redundancy	238
Bearings > Tolerance	3
Distances > Tolerance	9
Close Points Found	0
Line Points Found	0
Max Easting Shift	-17.206
Max Northing Shift	-25.805 (745)
Avg. Easting Shift	0.123
Avg. Northing Shift	-1.527
Avg. of Coordinate Residuals	1.24
Std. Deviation Coordinate Residuals	7.77
Adjustment Rank	4
Comments	Did not converge or stabilize. Failed after 4 iterations.
Number of control points	10
Number of control points inside	1
Number of control points outside	10
Lines within 2' of control layer	14
Total Number of Lines	60
Percent Match	23.33

The highest ranking sample was sample 4. The before and after images are included in Figure 16 and the adjustment statistics are shown in Table 9.

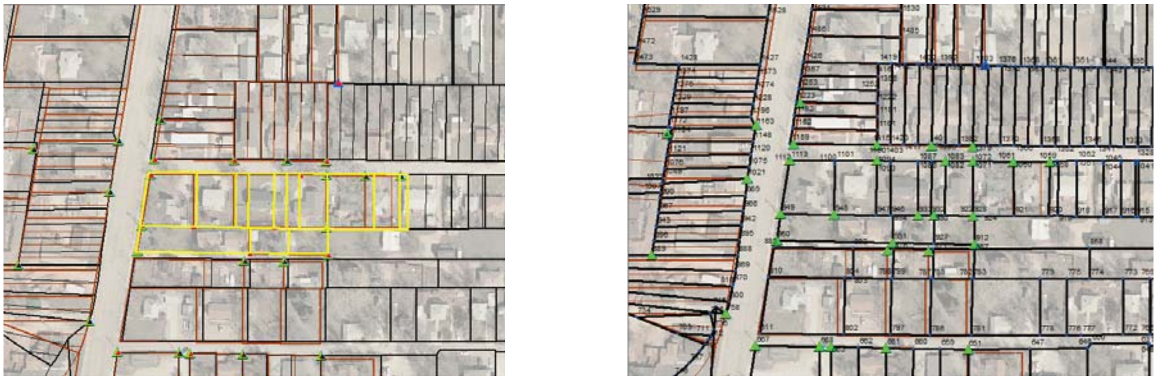


Figure 16. Sample 4 before adjustment was applied (left) and sample 4 after adjustment was applied (right).

Table 9. Sample 4 adjustment statistics.

Sample	**4 - (2)**
# Control Points	14
# Parcels	21
# Points	37
# Bearings	140
# Distances	140
#Unknowns	67
Redundancy	213
Bearings > Tolerance	0
Distances > Tolerance	0
Close Points Found	0
Line Points Found	0
Max Easting Shift	-9.885
Max Northing Shift	-10.016 (1060)
Avg. Easting Shift	-1.253
Avg. Northing Shift	-0.051
Avg. of Coordinate Residuals	0.77
Std. Deviation Coordinate Residuals	4.51
Adjustment Rank	1
Comments	
Number of control points	14
Number of control points inside	4
Number of control points outside	10
Lines within 2' of control layer	35
Total Number of Lines	36
Percent Match	97.22

A significant amount of improvement was made in the sample areas adjusted by adding additional control points and ensuring that they were well-distributed inside of and around the boundary of the area being adjusted.

Detailed information about each of the areas that was adjusted has been included in Appendix B.

4 Conclusion and Discussion

The parcel fabric data model provides a comprehensive way to manage cadastral information that can maintain historical parcel information in conjunction with detailed, survey information including geodetic coordinates. Once the cadastre has been created it can also be continuously improved over time and efficiently associated with parcel-based layers, as illustrated by the successful achievement of the objectives set forth in this study. These include (1) developing a feasible workflow for converting existing data (2) maintaining and improving the integrity of cadastre data over time and (3) the ability to integrate these data with related layers. This data model has provided Rapid City the ability to improve their digital cadastre with a limited amount of resources. Understanding that care should be used when adjusting data of unknown or poor quality, it has been suggested to Rapid City that as long as the adjustments being made are checked against information of known good quality, this is a reasonable way to move forward and improve the quality of their existing data.

Land records information has historically been stored in GIS databases by individual components: points, lines and polygons. One distinct weakness of this data model has been its inability to associate line and point features to the polygons they represented. There was also no efficient process or method that allowed for new improved data to be incorporated, making it difficult to update property-dependent layer. In addition, distributing error for plat misclosures (Bunten 2008) was also challenging. The parcel fabric data model has addressed these shortcomings resulting in a living land records system that is robust and more efficient to maintain and update.

Not only is it important to have a digital parcel dataset for assessing and collecting taxes and tracking land ownership, it is also becoming increasingly necessary that the accuracy and accessibility of land records information be improved for better resource management (Folger 2009), national security (Enemark 2010), critical infrastructure (Harper 2006) and emergency response efforts (Binge 2010). As pointed out by Brown & Moyer (1989), land is one of the most fundamental resources and historically, records of this resource have been poor. However, as growth and development continue to occur, restricting the availability and challenging the resilience of this resource, having up-to-date and accurate information will be critical for the decision-making process. Craig and Wahl (2003) contend that by having accurate spatial representations of land in a GIS "the decisions about the locations of improvements and resources on the land will not be subject to costly errors and assumptions." One example of a community striving to improve the management of their land resources by developing a seamless parcel dataset is highlighted by Bunten (2008). The City of Duluth, Minnesota embarked on a five-year project to "actively try to better manage development, its infrastructure and protect the natural environment, including the Lake Superior watershed." (Bunten 2008) This project was undertaken prior to the introduction of the parcel fabric data model and some of the challenges of working with land records information as individual components (points, lines and polygons), as highlighted above, were encountered. The workflow developed during this study could easily be applied by a municipal organization, such as the City of Duluth.

Feedback in the form of telephone conversations with representatives from organizations that have implemented the parcel fabric (e.g. City of Denver, Colorado (Doug Genzer, August 2011) and City of Gillette, Wyoming (Nick Kenczka, February 23, 2011)) and the findings in this study reveal that one of the biggest challenges in migrating to the parcel fabric is preparing and loading existing data. The workflow developed during this study provides a means for systematically finding and addressing some of these pitfalls which will result in more efficient implementations. The accuracy assessment presented in this study also provides users with a means for identifying problems when applying adjustments in the parcel fabric and outlines steps that can be taken to correct these issues.

For several decades, there have been voices defending the need for a nation-wide cadastre in the United States (Foster 2008). While this has not been achieved to date, there have been successful state-wide cadastres built, which is a step towards the goal of developing a national seamless parcel database. One such example is the state of Montana where the average annual benefit of having accurate accessible land records information is in the million-dollar range (Zimmer 2007). This example highlights the cost-savings and efficiency realized by having an accurate, seamless dataset of land records. Country-wide digital seamless cadastral coverages of survey-grade accuracy have also been successfully developed. One such example is in New Zealand. Land Information New Zealand (LINZ) is an online seamless parcel data system that provides government officials, surveyors and the public with more than 150 years of titles, survey marks, plans, etc. resulting in a significant increase in efficiencies for title research, land transfers and filing of certified documents by surveyors. LINZ is supported by the New Zealand Institute of Surveyors and New Zealand Law Society (Richardson 2008). As more organizations adopt a common data model for storing land information, such as the parcel fabric, the effort of moving the United States of America towards a National Cadastral Dataset, as provided for in the National Spatial Data Infrastructure, will be strengthened.

Historically, surveyors have been remote from the GIS industry because GIS cadastral coverages were not representative of the precisions maintained by surveyors (Harper & Lee 2008). However, limitations in hardware and software that existed previously have largely been overcome. "Survey accuracy in a cadastral database encourages a mutually beneficial environment for both surveyors and GIS professionals." (Harper & Lee 2008) The development of a national parcel database would provide an opening for surveyors to be leaders in geospatial technology by viewing their work as a societal resource rather than a proprietary asset (Jones 2010).

4.1 Future work and recommendations

The workflow that was developed during this study was an iterative process that included significant involvement from the end user (Figure 17) at each step, resulting in a process that can be implemented immediately. In fact, the workflow developed here is currently being used by the City of

Rapid City to convert existing cadastral data to the parcel fabric. Since the workflow is generalized and quite scalable, it can be implemented elsewhere (with other data sets since the principle requirements are the same (i.e. develop a framework (step 1); prepare the data (step 2); adjustment of the data (step 3); quality checking through accuracy assessment (step 4); and adjustment of associated layer(s) (step5)). The workflow can be adopted by both large and small organizations managing land records information in both the public and private sectors. The applicability of this workflow is further supported by the response received at the GIS in the Rockies Conference 2011, where this work was presented. Representatives from a variety of sectors, including local governments, utility companies, the software vendor (ESRI) and private corporations all expressed interest in the workflow that was developed.

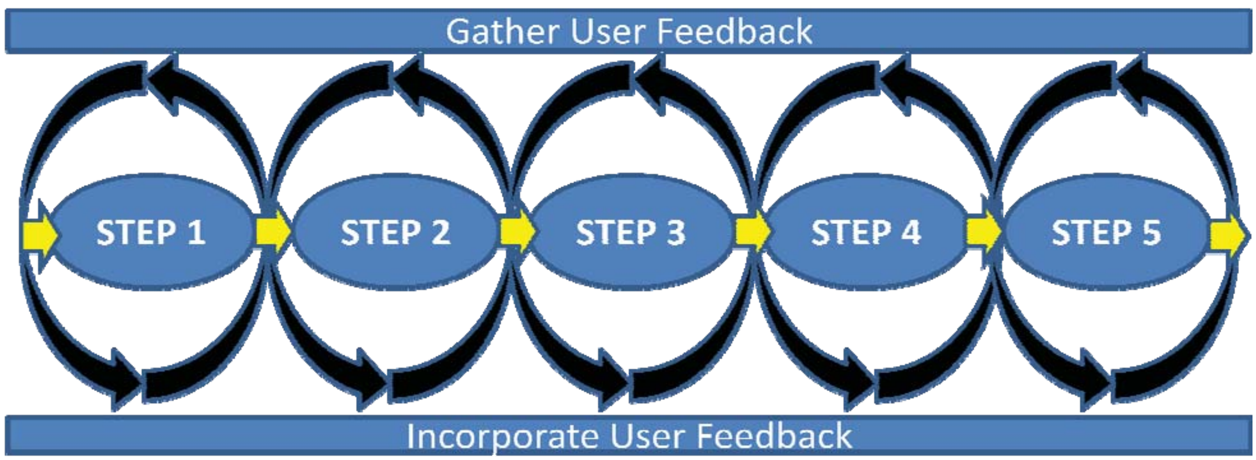


Figure 17. Interactive and iterative process used for testing workflow usability.

Even though the workflow created during this study can be widely applied, the next logical progression of work to be done on this project is developing a subsequent workflow for Rapid City to identify specific processes for handling daily tasks once the legacy data has been migrated to the parcel fabric. Some of these include integration of new land transactions into the fabric, adjusting parcels to control points, incorporating newly acquired control points, refining cartographic elements (e.g. dimension annotation, parcel labels, etc.) and publishing the parcels dataset via a web-mapping interface for end-user consumption.

5 References

Bhowmick, A., Bodnar, N., Farmer, D., Tirunagari, P., & Van Pelt, D. (2008). Cadastre Management the GIS Way. *Professional Surveyor Magazine, Volume 28, Issue 8.* Retrieved April 8, 2001 from http://www.profsurv.com/magazine/article.aspx?i=2198

Binge, M. L. (2010). Surveying GIS: The National Cadastre. *Point of Beginning.* Retrieved April 12, 2011 from http://www.pobonline.com/Articles/Column/BNP_GUID_9-5-2006_A_10000000000000857492

Brown, P. & Moyer, D. (1989). *Multipurpose Land Information Systems: The Guidebook.* Federal Geodetic Control Committee. Retrieved September 30, 2011 from http://www.ngs.noaa.gov/FGCS/tech_pub/Guidebook1of3.pdf

Bunten, R. (2008). Duluth Digital Plat & Parcel Development for Lake Superior Watershed Program. *Minnesota's Lake Superior Coastal Program.* Retrieved September 26, 2011 from http://www.scribd.com/doc/28107114/Duluth-Digital-Plat-Parcel-Development-for-Lake-Superior-Watershed-Protection-306-12-08

Capobianco, K.M. & Mann, W.C. (2009). Landbase Accuracy with Cadastral Editor. Government Engineering. Jan-Feb 2009: 20-21. http://www.govengr.com/ArticlesJan09/jacksonville.pdf

Craig, B. & Wahl, J. (2003). Cadastral Survey Accuracy Standards. *Surveying and Land Information Science, Volume 63, Number 2, pp. 87-106.*

Denver GIS Division. (2011). Telephone communication with Doug Genzer. City of Denver, Colorado.

Elfick, M. & Hodson, T. (2006). Managing Cadastral Data in a GIS. *Shaping the Change: XXIII FIG Congress Proceedings.* Retrieved April 12, 2011 from http://www.geodata.com.au/downloads/FIG2006_Managing%20Cadastral%20Data%20in%20a%20GIS.pdf

Elfick, M.H. (2006a). Cadastral Surveyors Time to Go Forward Digitally and Coordinate Accurately. *ESRI International Users Conference Proceedings – 2006.* Retrieved May 15, 2011 from http://proceedings.esri.com/library/userconf/proc06/papers/papers/pap_2138.pdf

Enemark, S. (2010). Land Governance: Responding to Climate Change, Natural Disasters, and the Millennium Development Goals. *Surveying and Land Information Science, Volume 70, Number 4, pp. 197-209.*

ESRI (2010). Curves and Lines. *SDK Sample Add-In*. Retrieved June 11, 2011 from http://resources.arcgis.com/gallery/file/arcobjects-net-api/details?entryID=3F5A0E12-1422-2418-A0DB-BA23CB137515

ESRI (2011). Desktop 10 Help. *ArcGIS Resource Center Desktop 10*. Retrieved May 18, 2011 from http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html

ESRI (2011a). Loading Data into a Parcel Fabric. *An ESRI White Paper.* Retrieved May 25, 2011 from http://www.esri.com/library/whitepapers/pdfs/loading_data_parcel_fabric.pdf

ESRI UK (n.d.). Centrally Locate and Manage Your Survey Data. Retrieved May 24, 2011 from http://www.esriuk.com/products/showproduct.asp?prodid=47&groupid=7&activetab=&mode=keyfeatures

ESRI & Kaufmann, J (2004). ArcGIS Cadastre 2014 Data Model Vision. http://www.esri.com/industries/cadastre/pdf/nc_2014.pdf

FIG (International Federation of Surveyors) (2009). Cadastral Template. *A Worldwide Comparison of Cadastral Systems.* Retrieved August 12, 2011 from http://www.fig.net/cadastraltemplate/fielddata/d1.htm

Folger, Peter (2009). Issues Regarding a National Land Parcel Database. *Congressional Research Service.* Retrieved October 19, 2011 from http://www.fas.org/sgp/crs/misc/R40717.pdf

Foote, K. & Huebner, D. (1995). Error, Accuracy, and Precision. *The Geographer's Craft.* Retrieved from http://www.colorado.edu/geography/gcraft/notes/error/error_f.html

Foster, R. (2008). A National Cadastre for the U.S.? *Point of Beginning.* Retrieved June 12, 2011 from http://www.pobonline.com/Articles/Column/BNP_GUID_9-5-2006_A_10000000000000476418

Genzer, D. & Tessar, P. (2011). *Migrating the DenverGIS Cadastral Coverages to the Parcel Fabric. Presented at 2011 ESRI International User Conference. San Diego, USA. Jul 12, 2011.* http://events.esri.com/uc/2011/infoweb/onlineagenda/index.cfm?fa=ofg_details_form&ScheduleID=79

Geodata (2006). Cadastral Management Solutions: A Strategy For A Gradual Upgrade To A Survey Accurate GIS Cadastral Database. *Geodata Information Systems.* Retrieved June 5, 2011 from http://www.geodata.com.au/downloads/Gradual%20Upgrade%20Strategy%20Dec%2006.pdf

Geodata (2010). Survey & Cadastral database management. Appendix D. Case Studies. http://www.geodata.com.au/downloads/GA%20COMPANY%20PROFILE-App_D-Case%20Studies-SEPTEMBER_2010.pdf

Goodchild, M. (1992). Sharing Imperfect Data. *NCGIS Initiative 9: Institutions Sharing Spatial Information Meeting.* Retrieved June 22, 2011 from http://www.geog.ucsb.edu/~good/papers/228.pdf

Harper, I. (2006). Survey Accurate Parcel Networks as the Base Layer for Enhanced GIS. *ESRI Survey and GIS Summit – Paper 2436* Retrieved June 4, 2011 from http://www.geodata.com.au/downloads/ESRI%20UC%20Paper%202436%20-%20Ian%20Harper.pdf

Harper, I. & Lee, R. (2008). New GIS Based Cadastral Precision Efficiencies. *GIS Development*. Retrieved April 16, 2011 from http://www.gisdevelopment.net/magazine/global/2008/july/32.htm

Huong, D. (2010). The application of ArcGIS cadastral frabric model for cadastral database management. Presented at the International Symposium on Geoinformatics for Spatial Infrastructure Development in Earth and Allied Sciences. http://wgrass.media.osaka-cu.ac.jp/gisideas10/viewpaper.php?id=383

International Association of Assessing Officers (IAAO) (2009). Standard on Digital Cadastral Maps and Parcel Identifiers – 2009. Retrieved August 14, 2011 from http://www.iaao.org/uploads/StandardonManualCadastralMaps.pdf

Jones, B. (2010). National Land Parcel Database and Surveyors. *Professional Surveyor Magazine, Volume 30, Issue 10* Retrieved April 9, 2011 from http://www.profsurv.com/magazine/article.aspx?i=70809

Kaufmann, J. & Steudler, D. (1998). *Cadastre 2014 - A Vision for a Future Cadastral System.* Paper and Presentation at Technical Session 7, XXI FIG-Congress, Brighton, July 1998. http://www.fig.net/cadastre2014/

Kennedy, E.A. & Ritchie, R.G. (1982). *Mapping the Urban Infrastructure.* Paper presented at the Fifth International Symposium on Computer-Assisted Cartography, August 1982. Retrieved August 12, 2011 from http://mapcontext.com/autocarto/proceedings/auto-carto-5/pdf/mapping-the-urban-infrastructure.pdf

Konecny, G. (2011). A Geocoded Cadastral Fabric As Precondition For A Sustainable Land Management System. *GIS Ostrava 2011 Symposium Proceedings.* Retrieved May 4, 2011 from http://gis.vsb.cz/GIS_Ostrava/GIS_Ova_2011/sbornik/papers/Konecny.pdf

Moran, T., Herrmann, M., & Hodson, T. (2008). *The ArcGIS Cadastral Fabric Data Model. Presented at 2008 ESRI International User Conference. San Diego, CA USA. Aug 2008.* http://www.scdhec.gov/gis/presentations/ESRI_Conference_08/tws/workshops/tw_1058.pdf

Palatiello, J. M. (2008). Capitol Gains: A National Parcel Cadastre. *Point of Beginning.* Retrieved April 16, 2011 from http://www.pobonline.com/Articles/Column/BNP_GUID_9-5-2006_A_10000000000000361684

Rapid City GIS Division. (2009). Rapid City Corporate Limits [metadata]. City of Rapid City, South Dakota: GIS Division.

Richardson, K. (2008). Out with Paper. *Professional Surveyor Magazine, Volume 28, Issue 9.* Retrieved April 9, 2011 from http://www.profsurv.com/magazine/issue.aspx?i=144

Robillard, W., Wilson, D. and Brown, C. (2011). *Evidence and Procedures for Boundary Location.* Hoboken, NJ: John Wiley Sons, Inc.

Southern Illinois University Carbondale (2010). Course Lecture Notes. Retrieved May 11, 2011 from http://civil.engr.siu.edu/surveying/classes/LandSurveying.ppt

United States Geological Survey (USGS) (1947). National Map Accuracy Standards. Retrieved August 10, 2011 from http://rockyweb.cr.usgs.gov/nmpstds/nmas647.html

Zimmer, R. J. (2007). Surveyors Working to Improve GIS. *The American Surveyor.* Retrieved April 9, 2011 from http://www.amerisurv.com/content/view/3764/150

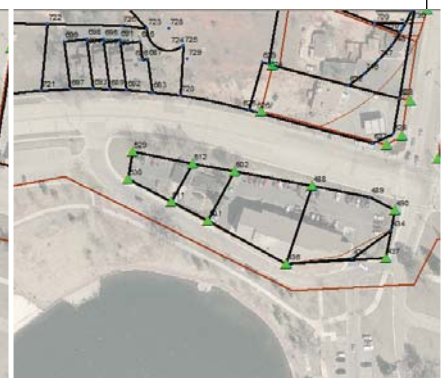
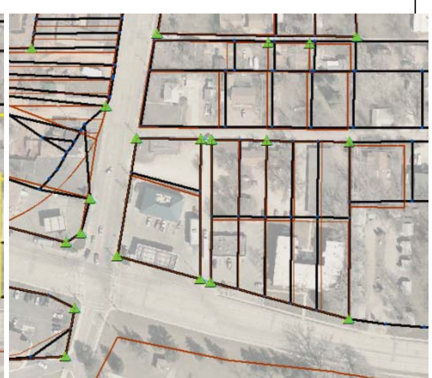
6 Appendix

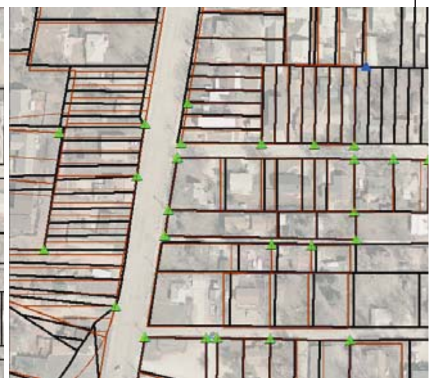
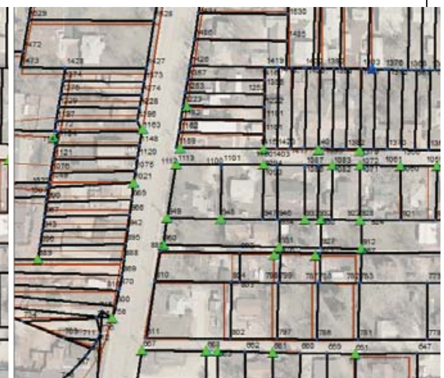
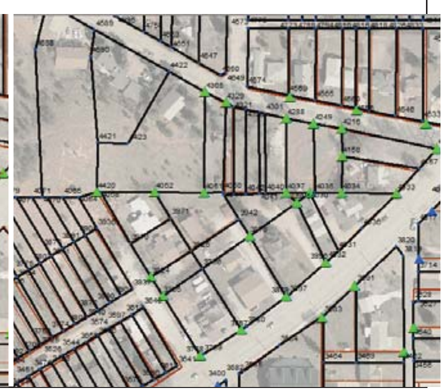
6.1 Appendix A. Least –squares adjustment in the parcel fabric

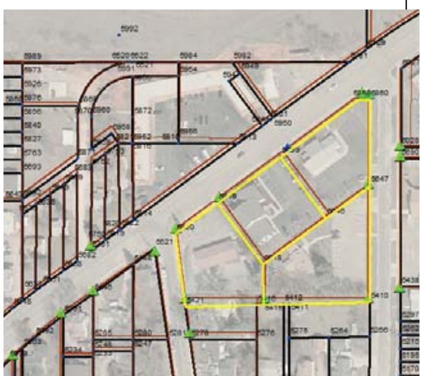
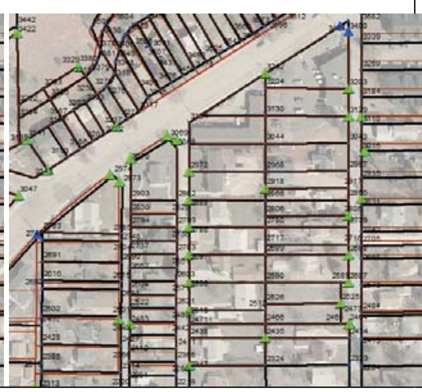
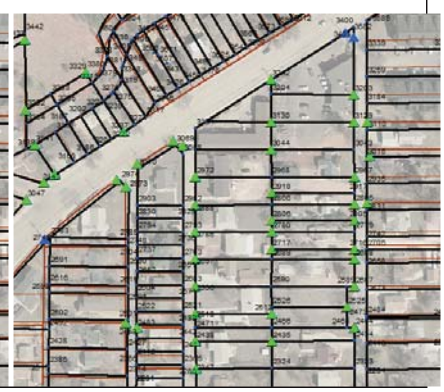
http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/About_the_fabric_least_squares_adjustment/001t0000014p000000/

6.2 Appendix B. Adjustment results

Figure 18. Each map represents a sample area either before any adjustment was applied or after the first and second adjustments and any associated changes were executed. The yellow and black lines represent Rapid City parcels that were imported into the parcel fabric (yellow is just black highlighted and represents the area being adjusted) and the brown lines represent the AutoCAD control layer. Green triangles are control points.

Sample 1 – Before Adjustment	Sample 1 –1^{st} Adjustment	Sample 1 – 2^{nd} Adjustment
		
Sample 2 – Before Adjustment	Sample 2 –1^{st} Adjustment	Sample 2 – 2^{nd} Adjustment
		
Sample 3 – Before Adjustment	Sample 3 –1^{st} Adjustment	Sample 3 – 2^{nd} Adjustment
		

Sample 4 – Before Adjustment	Sample 4 – 1st Adjustment	Sample 4 – 2nd Adjustment
		
Sample 5 – Before Adjustment	Sample 5 – 1st Adjustment	Sample 5 – 2nd Adjustment
		
Sample 6 – Before Adjustment	Sample 6 – 1st Adjustment	Sample 6 – 2nd Adjustment
		

Sample 7 – Before Adjustment	Sample 7 – 1st Adjustment	Sample 7 – 2nd Adjustment
		
Sample 8 – Before Adjustment	Sample 8 – 1st Adjustment	Sample 8 – 2nd Adjustment
		
Sample 9 – Before Adjustment	Sample 9 – 1st Adjustment	Sample 9 – 2nd Adjustment
		

Sample 10 – Before Adjustment	Sample 10 –1st Adjustment	Sample 10 – 2nd Adjustment
		
Sample 11 – Before Adjustment	Sample 11 – 1st Adjustment	Sample 11 – 2nd Adjustment
		
Sample 12 – Before Adjustment	Sample 12 – 1st Adjustment	Sample 12 – 2nd Adjustment
		

Table 10. Description of Sample 1 and results of adjustment

Sample	**1 - (Pre)**	**1 - (1)**	**1 - (2)**
# Control Points		6	10
# Parcels		8	8
# Points		12	12
# Bearings		35	35
# Distances		35	35
# Unknowns		20	12
Redundancy		50	58
Bearings > Tolerance		0	0
Distances > Tolerance		2	2
Close Points Found		0	0
Line Points Found		0	0
Max Easting Shift		-8.562	2.95
Max Northing Shift		11.906 (511)	-4.220 (489)
Avg. Easting Shift		0.175	2.379
Avg. Northing Shift		6.35	-2.957
Avg. of Coordinate Residuals		1.45	1.6
Std. Deviation Coordinate Residuals		5.84	6.43
Adjustment Rank		3	1
Comments			
Number of control points		6	10
Number of control points inside		0	0
Number of control points outside		6	10
Lines within 2' of control layer	2	11	16
Total Number of Lines	17	17	17
Percent Match	11.76	64.71	94.12

Table 11. Description of Sample 2 and results of adjustment

Sample	**2 - (Pre)**	**2 - (1)**	**2 - (2)**
# Control Points		9	12
# Parcels		25	23
# Points		35	35
# Bearings		134	125
# Distances		134	125
# Unknowns		77	69
Redundancy		191	181
Bearings > Tolerance		0	0
Distances > Tolerance		0	0
Close Points Found		0	0
Line Points Found		0	0
Max Easting Shift		3.971	5.712
Max Northing Shift		-1.682 (479)	-5.658 (588)
Avg. Easting Shift		1.766	1.376
Avg. Northing Shift		-0.199	0.972
Avg. of Coordinate Residuals		0.21	0.48
Std. Deviation Coordinate Residuals		1.08	2.85
Adjustment Rank		3	2
Comments			
Number of control points		9	12
Number of control points inside		0	3
Number of control points outside		9	9
Lines within 2' of control layer	6	23	31
Total Number of Lines	38	38	38
Percent Match	15.79	60.53	81.58

Table 12. Description of Sample 3 and results of adjustment

Sample	**3 - (Pre)**	**3 - (1)**	**3 - (2)**
# Control Points	[redacted]	10	10
# Parcels	[redacted]	21	26
# Points	[redacted]	53	54
# Bearings	[redacted]	143	176
# Distances	[redacted]	143	176
# Unknowns	[redacted]	107	114
Redundancy	[redacted]	179	238
Bearings > Tolerance	[redacted]	3	3
Distances > Tolerance	[redacted]	8	9
Close Points Found	[redacted]	0	0
Line Points Found	[redacted]	0	0
Max Easting Shift	[redacted]	-17.849	-17.206
Max Northing Shift	[redacted]	-25.350 (745)	-25.805 (745)
Avg. Easting Shift	[redacted]	-0.221	0.123
Avg. Northing Shift	[redacted]	-1.551	-1.527
Avg. of Coordinate Residuals	[redacted]	1.11	1.24
Std. Deviation Coordinate Residuals	[redacted]	7.02	7.77
Adjustment Rank	[redacted]	4	4
Comments	[redacted]	Did not converge or stabilize	Did not converge or stabilize. Failed after 4 iterations.
Number of control points	[redacted]	10	10
Number of control points inside	[redacted]	1	1
Number of control points outside	[redacted]	9	10
Lines within 2' of control layer	3	13	14
Total Number of Lines	60	60	60
Percent Match	5.00	21.67	23.33

Table 13. Description of Sample 4 and results of adjustment

Sample	4 - (Pre)	4 - (1)	4 - (2)
# Control Points		8	14
# Parcels		20	21
# Points		36	37
# Bearings		133	140
# Distances		133	140
# Unknowns		76	67
Redundancy		190	213
Bearings > Tolerance		0	0
Distances > Tolerance		0	0
Close Points Found		0	0
Line Points Found		0	0
Max Easting Shift		-14.428	-9.885
Max Northing Shift		-13.140 (1060)	-10.016 (1060)
Avg. Easting Shift		-1.252	-1.253
Avg. Northing Shift		1.038	-0.051
Avg. of Coordinate Residuals		0.61	0.77
Std. Deviation Coordinate Residuals		4.53	4.51
Adjustment Rank		2	1
Comments			
Number of control points		8	14
Number of control points inside		0	4
Number of control points outside		10	10
Lines within 2' of control layer	9	30	35
Total Number of Lines	36	36	36
Percent Match	25.00	83.33	97.22

Table 14. Description of Sample 5 and results of adjustment

Sample	**Pre - (5)**	**5 - (1)**	**5 - (2)**
# Control Points		6	9
# Parcels		10	10
# Points		16	16
# Bearings		54	54
# Distances		54	54
# Unknowns		30	24
Redundancy		78	84
Bearings > Tolerance		0	0
Distances > Tolerance		0	0
Close Points Found		0	0
Line Points Found		0	0
Max Easting Shift		-2.132	6.595
Max Northing Shift		2.297 (1841)	-2.242 (1839)
Avg. Easting Shift		-0.163	0.675
Avg. Northing Shift		1.225	-0.171
Avg. of Coordinate Residuals		0.42	0.7
Std. Deviation Coordinate Residuals		2.17	3.43
Adjustment Rank		3	1
Comments			
Number of control points		6	9
Number of control points inside		0	3
Number of control points outside		6	6
Lines within 2' of control layer	2	12	18
Total Number of Lines	19	19	19
Percent Match	10.53	63.16	94.74

Table 15. Description of Sample 6 and results of adjustment

Sample	**Pre - (6)**	**6 - (1)**	**6 - (2)**
# Control Points		17	22
# Parcels		37	37
# Points		47	49
# Bearings		194	198
# Distances		194	198
# Unknowns		97	91
Redundancy		291	305
Bearings > Tolerance		0	0
Distances > Tolerance		0	0
Close Points Found		0	0
Line Points Found		0	0
Max Easting Shift		10.251	11.796
Max Northing Shift		13.328 (4058)	11.650 (3997)
Avg. Easting Shift		0.652	-0.915
Avg. Northing Shift		3.092	2.067
Avg. of Coordinate Residuals		0.47	0.73
Std. Deviation Coordinate Residuals		2.46	3.62
Adjustment Rank		4	3
Comments			did not converge but stabilized at +/- 3'
Number of control points		17	22
Number of control points inside		4	8
Number of control points outside		14	14
Lines within 2' of control layer	6	30	43
Total Number of Lines	63	63	63
Percent Match	9.52	47.62	68.25

Table 16. Description of Sample 7 and results of adjustment

Sample	**Pre - (7)**	**7 - (1)**	**7 - (2)**
# Control Points		8	9
# Parcels		17	18
# Points		32	38
# Bearings		98	102
# Distances		98	102
# Unknowns		65	78
Redundancy		131	126
Bearings > Tolerance		0	0
Distances > Tolerance		0	0
Close Points Found		0	0
Line Points Found		0	0
Max Easting Shift		7.563	7.746
Max Northing Shift		-15.449 (3317)	-15.118 (3317)
Avg. Easting Shift		0.524	0.757
Avg. Northing Shift		-0.717	-0.424
Avg. of Coordinate Residuals		0.7	0.59
Std. Deviation Coordinate Residuals		4.45	4.06
Adjustment Rank		2	2
Comments			
Number of control points		8	9
Number of control points inside		1	1
Number of control points outside		7	7
Lines within 2' of control layer	30	34	34
Total Number of Lines	41	41	41
Percent Match	73.17	82.93	82.93

Table 17. Description of Sample 8 and results of adjustment

Sample	Pre - (8)	8 - (1)	8 - (2)
# Control Points		8	10
# Parcels		8	7
# Points		14	14
# Bearings		44	37
# Distances		44	37
# Unknowns		20	15
Redundancy		68	59
Bearings > Tolerance		0	0
Distances > Tolerance		0	0
Close Points Found		0	0
Line Points Found		0	0
Max Easting Shift		1.994	2.733
Max Northing Shift		2.903 (5699)	4.094 (5699)
Avg. Easting Shift		0.624	0.598
Avg. Northing Shift		0.511	1.915
Avg. of Coordinate Residuals		0.61	0.79
Std. Deviation Coordinate Residuals		3.35	4.38
Adjustment Rank		3	1
Comments			
Number of control points		8	10
Number of control points inside		0	3
Number of control points outside		7	7
Lines within 2' of control layer	0	12	16
Total Number of Lines	17	17	17
Percent Match	0.00	70.59	94.12

Table 18. Description of Sample 9 and results of adjustment

Sample	**Pre - (9)**	**9 - (1)**	**9 - (2)**
# Control Points		17	27
# Parcels		44	41
# Points		51	48
# Bearings		216	204
# Distances		216	204
# Unknowns		112	83
Redundancy		320	325
Bearings > Tolerance		0	0
Distances > Tolerance		0	0
Close Points Found		0	0
Line Points Found		0	0
Max Easting Shift		-0.546	-0.243
Max Northing Shift		1.179 (3130)	-0.567 (3133)
Avg. Easting Shift		-0.05	0.007
Avg. Northing Shift		0.073	-0.027
Avg. of Coordinate Residuals		0.16	0.17
Std. Deviation Coordinate Residuals		0.86	0.9
Adjustment Rank		1	1
Comments		did not converge but did stabilize at .005N/.006E	did not converge but did stabilize at .003N/.004E
Number of control points		17	27
Number of control points inside		2	8
Number of control points outside		15	21
Lines within 2' of control layer	41	40	40
Total Number of Lines	43	43	43
Percent Match	95.35	93.02	93.02

Table 19. Description of Sample 10 and results of adjustment

Sample	Pre - (10)	10 - (1)	10 - (2)
# Control Points		8	14
# Parcels		26	26
# Points		34	34
# Bearings		143	143
# Distances		143	143
# Unknowns		78	66
Redundancy		208	220
Bearings > Tolerance		4	4
Distances > Tolerance		0	0
Close Points Found		0	0
Line Points Found		0	0
Max Easting Shift		12.206	10.763
Max Northing Shift		-17.744 (4203)	-20.226 (4203)
Avg. Easting Shift		1.277	-0.182
Avg. Northing Shift		-0.035	-2.341
Avg. of Coordinate Residuals		0.86	0.93
Std. Deviation Coordinate Residuals		5.18	5.83
Adjustment Rank		3	3
Comments		did not converge or stabilize, but was within +/- 1'	
Number of control points		8	14
Number of control points inside		0	6
Number of control points outside		8	8
Lines within 2' of control layer	4	24	26
Total Number of Lines	39	39	39
Percent Match	10.26	61.54	66.67

Table 20. Description of Sample 11 and results of adjustment

Sample	**Pre - (11)**	**11 - (1)**	**11 - (2)**
# Control Points		9	15
# Parcels		24	24
# Points		31	31
# Bearings		122	121
# Distances		122	121
# Unknowns		68	56
Redundancy		176	186
Bearings > Tolerance		0	0
Distances > Tolerance		0	0
Close Points Found		0	0
Line Points Found		0	0
Max Easting Shift		-5.641	-4.834
Max Northing Shift		-11.105 (3214)	-12.647 (3214)
Avg. Easting Shift		-1.782	-0.43
Avg. Northing Shift		0.169	-2.872
Avg. of Coordinate Residuals		0.29	0.27
Std. Deviation Coordinate Residuals		1.69	1.55
Adjustment Rank		2	2
Comments			
Number of control points		9	15
Number of control points inside		0	6
Number of control points outside		9	9
Lines within 2' of control layer	11	33	34
Total Number of Lines	41	41	41
Percent Match	26.83	80.49	82.93

Table 21. Description of Sample 12 and results of adjustment

Sample	**Pre - (12)**	**12 - (1)**	**12 - (2)**
# Control Points		6	11
# Parcels		17	17
# Points		20	20
# Bearings		82	82
# Distances		82	82
# Unknowns		45	35
Redundancy		119	129
Bearings > Tolerance		0	0
Distances > Tolerance		0	0
Close Points Found		0	0
Line Points Found		0	0
Max Easting Shift		-2.085	4.025
Max Northing Shift		-8.930 (5488)	-8.895 (5488)
Avg. Easting Shift		-1.029	0.647
Avg. Northing Shift		-1.644	-1.018
Avg. of Coordinate Residuals		0.37	0.41
Std. Deviation Coordinate Residuals		1.8	2.12
Adjustment Rank		3	2
Comments			
Number of control points		6	11
Number of control points inside		0	3
Number of control points outside		6	8
Lines within 2' of control layer	4	15	23
Total Number of Lines	27	27	27
Percent Match	14.81	55.56	85.19

6.3 Appendix C. Workflow usability survey results

Rapid City Cadastral Workflow Survey – August 2011

Question:	1	2	3	4	5	Additional Comments
1.) Do you think the workflow developed works well for your group?	☑ Strongly agree	☐ Agree	☐ Neither agree nor disagree	☐ Disagree	☐ Strongly disagree	
2.) How satisfied are you with the workflow steps?	☑ Very satisfied	☐ Satisfied	☐ Neither satisfied nor unsatisfied	☐ Unsatisfied	☐ Very unsatisfied	
3.) Do you think the steps of the workflow are logically ordered?	☑ Strongly agree	☐ Agree	☐ Neither agree nor disagree	☐ Disagree	☐ Strongly disagree	
4.) Does the workflow capture sufficient detail?	☐ Very Sufficient	☑ Sufficient	☐ Neither sufficient nor insufficient	☐ Insufficient	☐ Very Insufficient	
5.) Will the workflow be easily implemented with little to no modifications?	☑ Very easily	☐ Easily	☐ Neither easy nor difficult	☐ Difficult	☐ Very difficult	
6.) Is it easy to understand and follow the workflow?	☑ Very easily	☐ Easily	☐ Neither easy nor difficult	☐ Difficult	☐ Very difficult	
7.) Do you think the documentation outlining the workflow is useful/sufficient?	☑ Strongly agree	☐ Agree	☐ Neither agree nor disagree	☐ Disagree	☐ Strongly disagree	

8.) Do you think the feedback you provided was sufficiently addressed and incorporated into the workflow?	☑ Strongly agree	☐ Agree	☐ Neither agree nor disagree	☐ Disagree	☐ Strongly disagree
9.) How satisfied were you with the feedback you received?	☑ Very satisfied	☐ Satisfied	☐ Neither satisfied nor unsatisfied	☐ Unsatisfied	☐ Very unsatisfied
10.) Do you think the workflow will allow you to successfully improve and maintain your cadastral data?	☑ Strongly agree	☐ Agree	☐ Neither agree nor disagree	☐ Disagree	☐ Strongly disagree
11.) How many times do you anticipate using this workflow?	☐ 1	☐ 2-5	☐ 6-10	☐ 11-15	☑ >15
12.) How familiar are you with ArcGIS?	☑ Very familiar	☐ Familiar	☐ Neither familiar nor unfamiliar	☐ Unfamiliar	☐ Not very familiar
13.) How familiar are you with Parcel Editor?	☐ Very familiar	☑ Familiar	☐ Neither familiar nor unfamiliar	☐ Unfamiliar	☐ Not very familiar
14.) Do you have any other feedback you would like to share?					