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Deanship of Graduate Studies and Scientific Research
Master of Civil Engineering

Georeferencing of Jordanian Cadastral Block Sheets in Palestine Using
a Boundary-Conditioned Least-Squares Approach:
A Case Study of Tammun

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Thesis submitted in partial fulfillment of the requirements for the degree
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ABSTRACT

This thesis addresses the positional and geometric inconsistencies between historical Jordanian cadastral settlement block sheets and modern surveying data in Palestine. These discrepancies result from limitations associated with historical paper maps, including surveying and drafting errors, paper distortion, limited positional control, and differences between historical and modern coordinate reference systems. The methodology was applied to six connected cadastral blocks in the Tammun study area (Blocks 51, 53, 54, 56, 57 and 58). Valid cadastral features such as stone boundary walls, iron markers and cadastral crosses were identified by reviewing historical block sheets in paper and digital form and conducting field surveys. First, each block was georeferenced independently using different transformation models, and then a boundary-conditioned least-squares adjustment was applied using common Tie Points and shared-boundary relationships. A total of 540 Ground Control Points and 85 Control Tie groups were used for parameter estimation in the final network solution. In addition, 166 Ground Check Points and 12 Check Tie Point (CTP) groups were reserved for independent validation. The combined network RMSE for the third-order polynomial (Poly3) solution was 0.7030 m, while the independent Ground Check Point RMSE2D was 0.7884 m. The Control Tie RMSE was reduced from 1.5426 m to 0.8682 m, representing a 43.7% improvement, while the RMSE2D of the 12 withheld CTP groups was reduced from 1.7771 m to 1.0788 m, representing a 39.3% improvement in independent inter-block agreement. Poly3 achieved the lowest combined network RMSE and the highest proportional CTP improvement, whereas Poly2 achieved the lowest final withheld CTP RMSE2D of 1.0352 m. The results indicate that the proposed adjustment improves pointwise continuity between adjacent cadastral blocks and that model selection should be based on both internal fit and independent validation. The proposed approach provides a consistent technical basis for integrating historical cadastral data into GIS and supporting activities such as boundary re-establishment, land settlement and cadastral modernization in Palestine.

Keywords: cadastral maps, Geographic Information System (GIS), Jordanian settlement, coordinate systems, Palestine, tie points, boundary-conditioned least squares.

ربط إحدائيات مخططات أحواض التسوية الأردنية في فلسطين باستخدام منهج المربعات الصغرى
المشروط بحدود الأحواض:
دراسة حالة في منطقة طمون
محمود إسماعيل نجار

الملخص

تهدف هذه الرسالة إلى معالجة الفجوات والاختلافات الموضوعية والهندسية بين مخططات أحواض التسوية الأردنية القديمة ونتائج أعمال المساحة الحديثة في فلسطين. وتُعزى هذه الفروقات بصورة رئيسة إلى أوجه القصور المرتبطة بالخرائط الورقية التاريخية، بما في ذلك أخطاء الرفع والرسم المساحي، وتشوه الورق، وضعف الضبط المكاني، والاختلافات بين أنظمة الإحدائيات التاريخية والحديثة. وقد طُبقت المنهجية على ستة أحواض تسوية مترابطة في منطقة طمون، وهي الأحواض 51 و53 و54 و56 و57 و58.

تبدأ الرسالة بجمع وتحليل مخططات أحواض التسوية الأردنية بصيغتها الورقية والرقمية، ثم تحديد المعالم العقارية والميدانية التي يمكن الاعتماد عليها. وبعد ذلك، تُفُذت أعمال مسح ميداني لتحديد وقياس معالم واضحة، مثل الجدران الحجرية الفاصلة، والعلامات الحديدية، والصلبان المساحية. وبعد جمع البيانات الميدانية، جرى إسناد كل حوض بصورة منفصلة باستخدام عدة نماذج للتحويل، ثم تقييم الدقة الموضوعية الناتجة ومقارنتها.

وفي الخطوة التالية، تم تنفيذ ضبط مشترك للأحواض المتجاورة باستخدام نقاط الربط والعلاقات بين النقاط الواقعة على الحدود المشتركة، وذلك من خلال طريقة مربعات الأخطاء الصغرى المشروطة بحدود الأحواض. واستُخدمت في الحل الشبكي النهائي 540 نقطة ضبط أرضية و85 مجموعة من نقاط الربط الضابطة لتقدير معاملات التحويل، في حين تم الاحتفاظ بـ166 نقطة فحص أرضية و12 مجموعة من نقاط فحص الربط لإجراء تحقق مستقل من نتائج الحل.

تم تقييم أداء الطريقة المقترحة استنادًا إلى الدقة الموضوعية، والفروقات عند نقاط الربط، ونتائج نقاط الفحص المستقلة. وبلغ الخطأ الجذري التربيعي الكلي للشبكة باستخدام نموذج كثير الحدود من الدرجة الثالثة (Poly3) مقدار 0.7030 م، في حين بلغ الخطأ الجذري التربيعي ثنائي الأبعاد لنقاط الفحص الأرضية المستقلة 0.7884 م. كما انخفض الخطأ الجذري التربيعي لنقاط الربط الضابطة من 1.5426 م إلى 0.8682 م، بنسبة تحسن بلغت 43.7%، بينما انخفض الخطأ الجذري التربيعي ثنائي الأبعاد لمجموعات نقاط فحص الربط الاثنيتي عشرة المستبعدة من الحل من 1.7771 م إلى 1.0788 م، بنسبة تحسن بلغت 39.3% في التطابق المستقل بين الأحواض. وحقق نموذج Poly3 أدنى خطأ جذري تربيعي كلي للشبكة وأعلى نسبة تحسن في نقاط فحص الربط، في حين حقق نموذج Poly2 أدنى قيمة نهائية للخطأ الجذري التربيعي ثنائي الأبعاد لنقاط فحص الربط المستبعدة، وبلغت 1.0352 م.

وتشير النتائج إلى أن طريقة الضبط المقترحة تحسن الاستمرارية الموضوعية والتطابق بين الأحواض المتجاورة، وأن اختيار نموذج التحويل يجب أن يعتمد على كل من جودة المطابقة الداخلية ونتائج التحقق المستقل. وفي النهاية، توفر هذه الرسالة أساسًا فنيًا أكثر تطابقًا لدمج البيانات العقارية التاريخية في نظم المعلومات الجغرافية، ودعم أعمال إعادة تثبيت الحدود، وتسوية الأراضي، وتحديث أنظمة السجل والمساحة العقارية في فلسطين.

الكلمات المفتاحية: الخرائط المساحية، نظم المعلومات الجغرافية، التسوية الأردنية، أنظمة الإحدائيات، فلسطين
نقاط الربط المشتركة، طريقة مربعات الأخطاء الصغرى المشروطة بحدود الأحواض.

DECLARATION

I declare that the Master Thesis entitled “Georeferencing of Jordanian Cadastral Block Sheets in Palestine Using a Boundary-Conditioned Least-Squares Approach: A Case Study of Tammun” is my own original work, and I hereby certify that unless stated, all work contained within this thesis is my own independent research and has not been submitted for the award of any other degree at any institution, except where due acknowledgement is made in the text.

Student Name: Mahmoud Ismaeel Najjar

Signature: _____

Date: _____

DEDICATION

I dedicate this achievement to my dear parents, with my deepest gratitude and affection. Their prayers, love, and constant support have been the foundation of my strength and success. They instilled in me a love of knowledge, perseverance, and steadfastness.

To my brothers and sisters, thank you for your constant presence, encouragement, love, and support, and for always being a source of strength and comfort.

To my dear wife, my steadfast supporter throughout this journey: you stood by me with patience, love, and understanding and shared the burdens of this stage with me; a significant share of this achievement belongs to you.

To my children, Tolen, Ismail, and Sarah, who fill my life with love, joy, hope, and aspiration. Your presence has inspired me to keep moving forward and to work toward a better future. I dedicate this success to you in the hope that one day it will be a source of inspiration and pride.

I am thankful to my colleagues and friends who have supported me throughout this journey with their sincere advice, kind words, and encouragement.

To my dear cousins, companions in cherished memories, bound to me by family and strengthened by years of shared experiences, I dedicate this accomplishment to you in appreciation of your love and valued presence in my life.

And to the soul of my cousin the heroic martyr Wadie Yahya Al-Najjar, whose good spirit, hopeful words, and encouragement inspired me to pursue my Master's degree before he ascended to the Gardens of Eternal Bliss, I dedicate this achievement to you in faithful remembrance and gratitude. Your words have been with me along this journey.

May Allah shower you with abundant mercy, grant you a place in His vast Paradise, and keep your cherished memory alive in our hearts.

I dedicate the fruit of this effort to all those who believed in me, who encouraged me, and who supported me during this journey.

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List of Abbreviations

CRS: Coordinate Reference System

EPSG: EPSG Geodetic Parameter Dataset / coordinate reference system identifier

FAO: Food and Agriculture Organization of the United Nations

FIG: International Federation of Surveyors

GCP: Ground Control Point

GCS: Geographic Coordinate System

GIS: Geographic Information System

GNSS: Global Navigation Satellite System

GPS: Global Positioning System

IOGP: International Association of Oil & Gas Producers

ISO: International Organization for Standardization.

ITRF: International Terrestrial Reference Frame.

LADM: Land Administration Domain Model.

PAL-GRF2023: Palestinian Geodetic Reference Frame 2023.

PCS: Projected Coordinate System.

PLA: Palestinian Land Authority.

RMSE: Root Mean Square Error

RRRs: Rights, Restrictions and Responsibilities

TM: Transverse Mercator

UTM: Universal Transverse Mercator

VHR: Very High Resolution

WGS84: World Geodetic System 1984

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List of Symbols

- x, y : Coordinates in the source (historical) map coordinate system.
- x', y' : Transformed coordinates in the target reference system.
- f, g : Transformation/condition functions used to relate source and target coordinates.
- a_i, b_i, c_i : Transformation coefficients or model parameters.
- t_x, t_y : Translation parameters in the x- and y-directions in the Helmert transformation.
- s : Uniform scale factor in the Helmert (similarity) transformation.
- θ : Rotation angle in the Helmert transformation.
- v_i : Residual associated with observation i .
- l : Observation/adopted-quantity vector.
- v : Residual vector.
- A : Design/Jacobian matrix; in the conditional model, partial derivatives with respect to the unknown coordinates.
- B : Jacobian matrix of condition functions with respect to observations or adopted quantities.
- x : Vector of unknown transformation parameters in the linear least-squares formulation.
- X : Vector of adjusted coordinates in the unified block adjustment.
- X_0 : Initial coordinate vector obtained from preliminary georeferencing.
- ΔX : Correction vector applied to the initial coordinates.
- w : Misclosure vector calculated at the approximate coordinates.
- Φ : Least-squares objective function (sum of squared residuals).
- r_i : Magnitude of the positional residual vector at point i .
- $\Delta x_i, \Delta y_i$: Residual components in the x- and y-directions at point i .
- e_x, e_y : Mean residual (bias) in the x- and y-directions.
- n : Number of observations or points, according to the equation in which it appears.
- i, j, k, p : Point or observation indices.
- T : Transpose operator.
- ∂ : Partial-derivative operator.

A, B (subscripts): Identifiers for adjacent cadastral block sheets in common-point conditions.

$r(X)$: Coordinate-residual vector used in the least-squares objective function.

$c(X)$: Vector of boundary-condition functions.

J_k : Jacobian matrix of the residual functions at iteration k .

C_k : Jacobian matrix of the boundary-condition functions at iteration k .

λ : Lagrange-multiplier vector in the constrained normal system.

k : Iteration index.

m : Number of tie points along a block interface.

$\Delta X_{t,p}^0$: Initial discrepancy vector between the two representations of tie point p .

d_p^0 : Initial planar separation at tie point p .

$RMSE_Tie^0$: Root-mean-square tie-point discrepancy before the simultaneous adjustment.

ϵ_X, ϵ_c : Convergence tolerances for coordinate corrections and boundary conditions.

θ_i, θ_j : Transformation-parameter vectors for adjacent blocks i and j .

w_t : Tie-point misclosure vector between two transformed occurrences of the same shared point.

d_t : Planar separation between the two transformed occurrences of a tie point.

f_x, f_y : Easting and northing tie-condition functions used to enforce shared-point coincidence.

$RMSE_x, RMSE_y$: Root-mean-square error components in the easting and northing directions.

$RMSE_r$: Combined horizontal root-mean-square error.

$A_adjusted, A_reference$: Adjusted and reference parcel areas used in parcel-area comparison.

$\Delta A\%$: Absolute percentage change in parcel area.

M : Denominator of the map scale used to convert paper-space quantities to ground-space quantities.

R : Scanning resolution in dots per inch (dpi).

σ_{point} : Approximate standard deviation of the final digitized cadastral point in ground units.

σ_{survey} : Standard deviation representing uncertainty inherited from the original field survey.

$\sigma_{\text{plot,paper}}$: Standard deviation associated with manual plotting on the paper sheet.

$\sigma_{\text{paper,local}}$: Standard deviation representing local nonuniform deformation of the historical paper.

$\sigma_{\text{dig,screen}}$: Standard deviation associated with point identification and digitization in the digital environment.

Chapter 1

Introduction

1.1 Background

Georeferencing historical cadastral blocks involves aligning historical cadastral maps with a current coordinate reference system so that their mapped positions can be compared with present-day ground locations. The study identifies features that appear on the historical maps and remain identifiable in the field, such as iron markers, cadastral crosses, and stone boundaries. These points are surveyed using GNSS. A portion of the dataset is used to georeference the maps, while the remaining observations are reserved for independent accuracy assessment.

Jordanian cadastral blocks are still widely used in Palestine for several land-related activities, including boundary definition, area calculation, and parcel subdivision. However, these maps were prepared many decades ago using the surveying and drafting methods available at that time. Their geometry may have been further affected by repeated copying and scanning, as well as by paper deterioration and deformation. As a result, the positions shown on the historical maps may not correspond exactly to those obtained from modern field measurements. Georeferencing each block independently may also result in small gaps or overlaps along shared boundaries. This mismatch between adjacent blocks represents the main problem addressed in this study.

In this study, each block is georeferenced independently, and the results obtained from different transformation methods are compared. Adjacent blocks are then evaluated using shared points and common boundaries to identify differences and improve agreement between them. The resulting dataset is intended to provide a more consistent basis for surveying and GIS applications.

1.2 Problem Statement

Ideally, the boundaries shown on cadastral block maps should agree closely with coordinates measured in the field. This is especially expected when modern GPS or GNSS equipment is used, since these instruments can provide centimeter-level accuracy. However, this level of agreement is not always achieved when working with historical Jordanian cadastral maps in Palestine.

The main issue is not the accuracy of the present-day field survey, but the condition and geometric quality of the old paper maps. These maps were prepared using surveying and drafting techniques that were less accurate than those available today. Their geometry may

also have changed over time because of paper expansion and shrinkage, environmental conditions, storage, repeated copying, and scanning. For this reason, even when accurate field coordinates are available, the boundaries taken from the historical maps may still contain positional differences.

The problem becomes clearer when neighboring blocks are georeferenced separately. A single block may appear acceptable when examined on its own, but differences can become visible when it is placed next to an adjacent block. These differences may appear as gaps, overlaps, or misalignments along the shared boundary. Such problems can affect boundary re-establishment, parcel area calculations, land subdivision, and the reliability of cadastral information.

In this thesis, each block is therefore evaluated in two ways: by comparing it with field-surveyed control points and by examining its agreement with neighboring blocks. The proposed method first georeferences the blocks using accurate field observations. It then adjusts neighboring blocks simultaneously using a boundary-conditioned least-squares approach.

1.3 Literature Review

Several previous studies have addressed the georeferencing of historical maps and the improvement of cadastral data through modern spatial techniques. These studies provide a scientific basis for understanding how old maps can be corrected, evaluated, and integrated into contemporary systems. At the same time, they indicate that the specific issue addressed in this thesis—namely, the simultaneous adjustment of neighboring Jordanian cadastral blocks in Palestine—has not yet received sufficient methodological attention (Sisman and Sisman, 2017; Sengupta et al., 2016; Forejt et al., 2020).

The Factors Optimization on Georeferencing Analog Maps

Sisman and Sisman (2017) investigated the factors affecting the accuracy of analog-map georeferencing. Their work showed that final positional accuracy depends on map scale, scanning resolution, and the number of common points. This study is relevant because it demonstrates that georeferencing accuracy is determined not only by the transformation model employed but also by map quality and the design of the georeferencing procedure. However, it focuses primarily on optimizing general georeferencing rather than solving a multi-block cadastral adjustment problem (Sisman and Sisman, 2017).

Constructing a Seamless Digital Cadastral Database Using Colonial Cadastral Maps and VHR Imagery

Sengupta and others (2016) proposed a methodology for generating an integrated digital cadastral database in India from colonial cadastral maps and very-high-resolution imagery. Their work demonstrated the value of merging historical maps with modern spatial data to create a more spatially continuous cadastral layer. This approach is closely related to the present study. However, this thesis differs in its emphasis on rigorous mathematical adjustment and on maintaining geometric alignment between adjacent blocks (Sengupta et al., 2016).

Historical Boundary Reconstruction and Digital Geospatial Conversion

Kral and others (2021) demonstrated how old boundary maps can be converted into usable digital spatial data when appropriate georeferencing and verification procedures are applied. Their study, which focused on urban boundary data rather than cadastral settlement blocks, supports a central premise of the present thesis: historical maps can still provide valuable spatial information if they are critically evaluated rather than transferred into digital form without assessment (Kral et al., 2021).

Digital Cadastral Map as Foundation of Coordinate-Based Cadastre

Cvijetinovic and others (2015) noted that analog cadastral maps should not be transferred directly into digital systems and treated as accurate coordinate documents without considering distortion, measurement limitations, and reference inconsistencies. This point is especially relevant in the Palestinian context, where Jordanian cadastral block sheets remain important in practice but require technical rehabilitation before reliable integration into a modern coordinate system (Cvijetinovic et al., 2015).

Quantifying Differences in Old Cadastral Maps

Forejt and others (2020) examined discrepancies in old cadastral maps and highlighted how such inconsistencies affect subsequent spatial analysis and land-use reconstruction. Their findings are important because historical cadastral maps should not be regarded as geometrically exact documents. Instead, their geometry should be examined and corrected before use in modern land applications (Forejt et al., 2020).

Modern Data Models for Cadastral Mapping

Hagemans and others (2022) proposed a modern cadastral data model for the Netherlands based on the Land Administration Domain Model. Although the Dutch context differs from the Palestinian context, the study reflects an international trend toward more structured, accurate, and digitally integrated cadastral systems. This thesis contributes to that broader

direction from the perspective of geospatial adjustment rather than data modeling (Hagemans et al., 2022).

Assessment of Geometric Accuracy of Jordanian Cadastral Maps in Palestine

The study by Tamim and Taha (2016) is one of the Palestinian studies most directly relevant to this thesis. They assessed the internal geometric accuracy of scanned Jordanian cadastral block maps in the West Bank using samples from Naqoor, Yamoona, and Silwad. The study examined grid-line marks, control points, registered distances, scanned-image distances, and GPS-measured historical marks. Drawing on local data rather than general theory, the study shows that Jordanian block sheets may contain significant geometric errors resulting from historical surveying practices, paper deformation, copying, and scanning (Tamim and Taha, 2016).

In the same study, the authors also tested several georeferencing transformations in ArcGIS, including affine, second-order polynomial, and spline transformations. They concluded that the second-order polynomial was generally the most promising option when sufficient control points, grid points, and field-measured historical marks were available. The approach, however, remained essentially a map-by-map georeferencing process. This limitation creates a clear methodological gap for the present thesis, which extends beyond individual sheet correction to the simultaneous adjustment of adjacent block sheets using shared points and common-boundary conditions (Tamim and Taha, 2016).

The reviewed studies demonstrate that historical maps and cadastral documents can remain useful when processed using appropriate technical methods. They also show that distortions, inconsistencies, and reference-system problems are common in old cadastral materials. In support of this argument, Tamim and Taha (2016) provide evidence from Palestine indicating that errors in Jordanian block sheets in the West Bank are large enough to affect their use in cadastral applications. Nevertheless, a clear gap remains regarding the simultaneous adjustment of neighboring Jordanian cadastral blocks in Palestine using a boundary-conditioned least-squares framework. This is the methodological gap addressed by the present study (Sisman and Sisman, 2017; Sengupta et al., 2016; Cvijetinovic et al., 2015; Forejt et al., 2020; Tamim and Taha, 2016).

1.4 Aim and Objectives

The main objective of this thesis is to develop and evaluate a georeferencing framework for historical Jordanian cadastral block sheets in Palestine based on a boundary-conditioned least-squares solution. The framework is designed to improve positional accuracy and

spatial consistency between adjacent cadastral blocks while providing a more reliable spatial basis for cadastral and GIS applications.

The specific objectives of this thesis are:

1. To assess the positional and geometrical discrepancies between historical Jordanian cadastral block sheets and modern field-survey observations.
2. To improve the positional accuracy of cadastral block and parcel boundaries using reliable Ground Control Points derived from modern surveying techniques.
3. To integrate common points and shared boundary features of adjacent cadastral blocks within a single simultaneous adjustment process.
4. To reduce positional discrepancies, gaps, overlaps, and mismatches along shared boundaries and thereby improve inter-block geometric consistency.
5. To compare the performance of independent block georeferencing with the proposed simultaneous boundary-conditioned adjustment using residuals, RMSE, independent Check Points, Control Tie Points, and withheld Check Tie Points.
6. To evaluate the performance of different transformation models, including similarity, affine, and polynomial transformations, within the proposed adjustment framework.
7. To establish a more consistent spatial framework for the subsequent assessment of parcel dimensions, areas, and boundary relationships within a GIS environment.
8. To provide a practical and transferable methodology for the rehabilitation, integration, and updating of historical cadastral records in Palestine.

1.5 Research Methodology

The method adopted in this thesis combines historical cadastral records, field surveying, and mathematical adjustment. The work begins with the collection of available paper and digital copies of the Jordanian cadastral block sheets. The study area is then selected based on the quality of the available data and the presence of identifiable field evidence that survives on the ground.

The first component shown in Figure 1.1 comprises the historical cadastral block sheets. The sheets are examined carefully to identify permanent or semi-permanent features that may serve as reference points. These may include cadastral crosses, iron markers, stone boundary lines, and other visible features that remain recognizable over time. This stage is important because the quality of the final adjustment depends heavily on the suitability of these linking points.

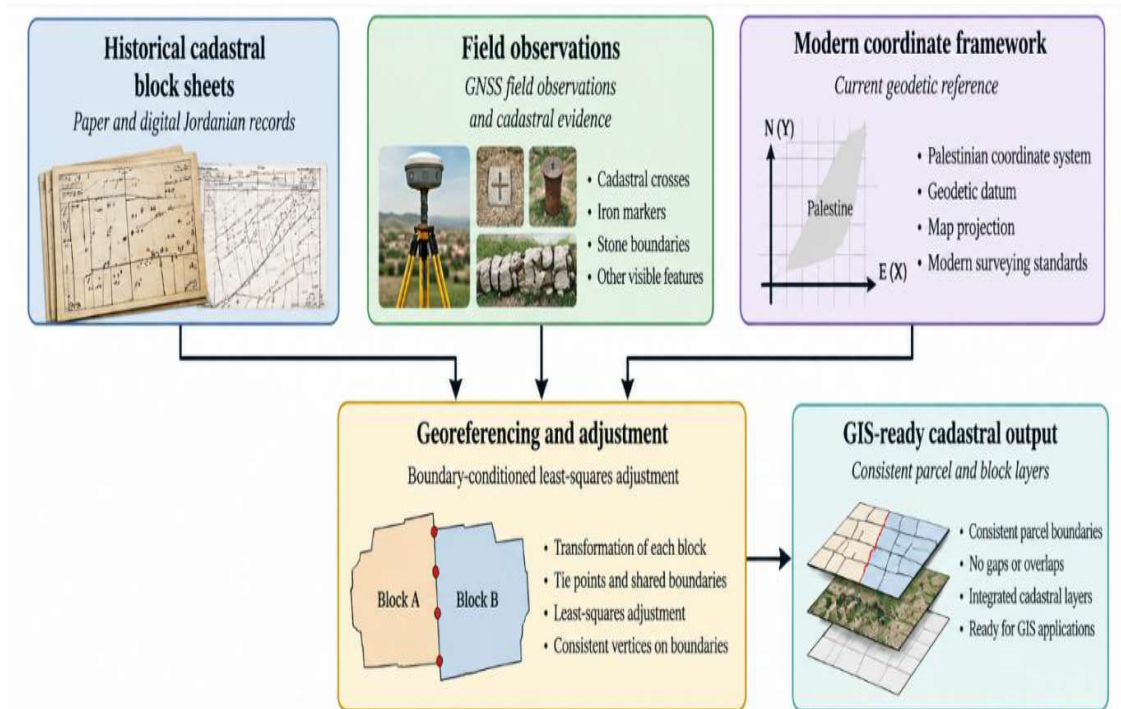


Figure 1.1. Relationship between historical cadastral sheets, field observations, and modern GIS-based outputs.

Source: Prepared by the researcher.

Subsequently, field observations are carried out using modern surveying instruments to obtain accurate coordinates for selected points and to establish a reliable present-day reference framework. Once the field data are collected, each cadastral block is examined individually to understand its local geometric behavior and principal distortion pattern.

The study then proceeds to the simultaneous-adjustment stage. At this stage, neighboring blocks are connected through tie points and shared-boundary points. These relationships are introduced into a boundary-conditioned least-squares model so that the transformed positions of corresponding vertices on adjacent blocks are estimated consistently. The expected benefit is a connected solution that reduces boundary mismatches while preserving agreement with the field control information.

Finally, the adjusted results are evaluated through residual analysis, positional comparison, and assessment of geometric consistency between adjacent cadastral blocks. This evaluation is used to determine whether the proposed adjustment improves the positional agreement of common points and reduces discontinuities along shared boundaries. The adjusted coordinates are then prepared for integration into GIS applications so that the rehabilitated cadastral data can support future engineering, cadastral, and land-administration activities. The overall methodology is shown in Figure 1.2 and follows a sequential workflow comprising the collection of historical cadastral sheets and field

observations, individual-block georeferencing and assessment, identification of tie points and shared boundaries, simultaneous boundary-conditioned adjustment, accuracy evaluation, and preparation of GIS-ready cadastral outputs.

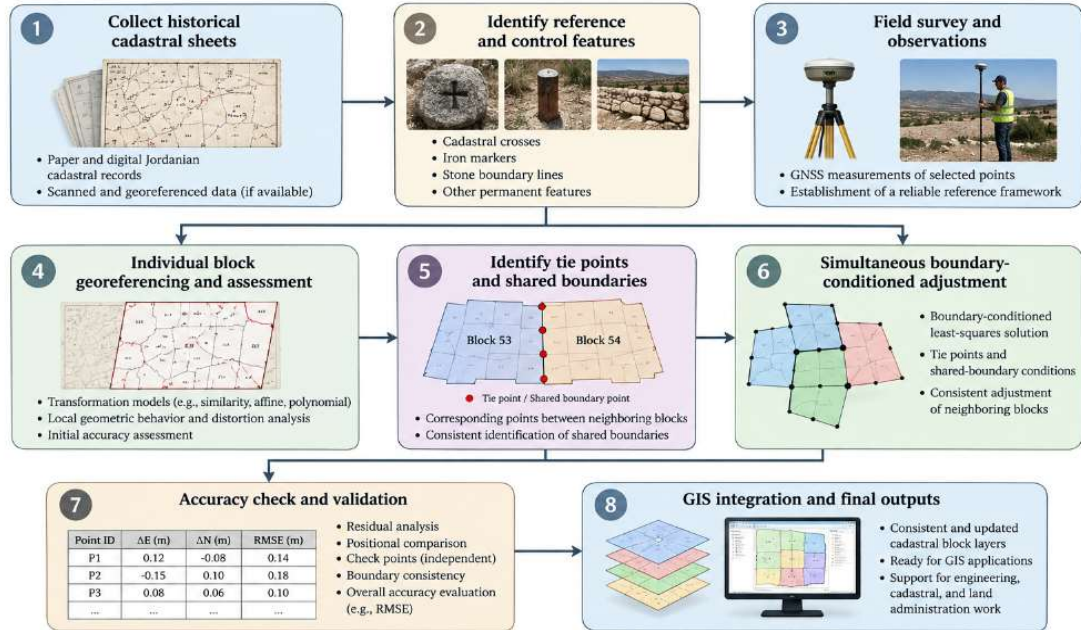


Figure 1.2. General workflow of the proposed methodology.

Source: Prepared by the researcher.

In addition to presenting the general workflow, it is important to distinguish between the conventional independent adjustment of individual cadastral blocks and the simultaneous adjustment approach proposed in this study. The independent adjustment process, in which each cadastral block is treated separately, is illustrated in Figure 1.3. This approach may provide acceptable local accuracy but can still result in positional differences, gaps, or overlaps along shared boundaries. In contrast, the proposed simultaneous adjustment treats neighboring blocks as parts of a connected cadastral system through tie points and shared-boundary points. This enables corresponding points along shared boundaries to be adjusted consistently within the same solution and thereby improves geometric continuity between adjacent blocks.

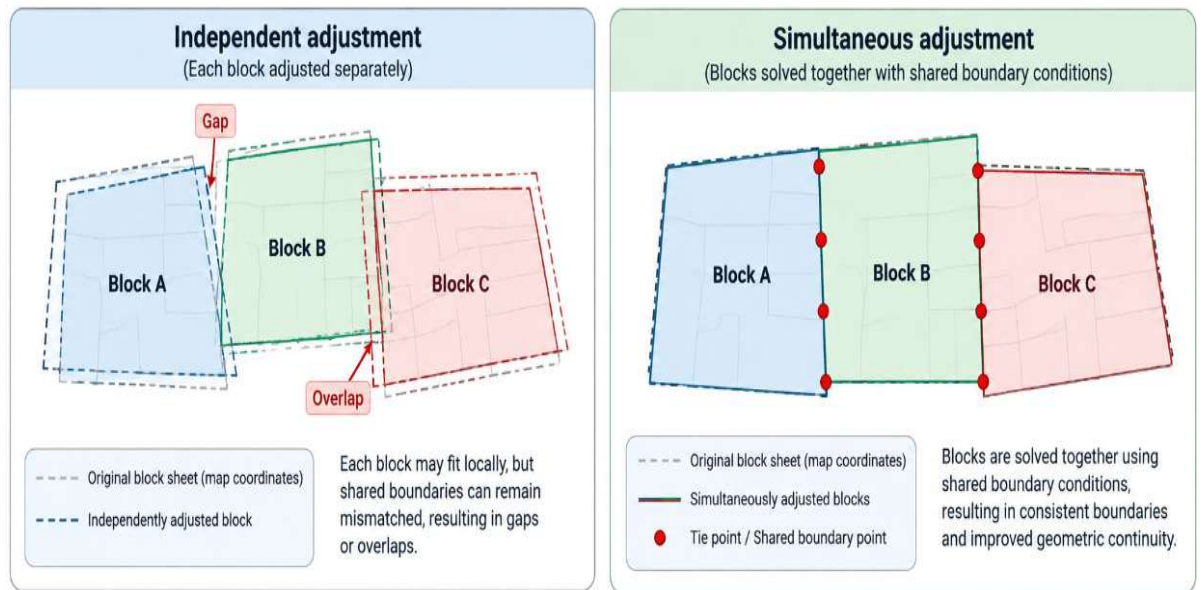


Figure 1.3. Conceptual comparison between independent adjustment and simultaneous adjustment.

Source: Prepared by the researcher.

1.6 Scientific Contribution

The scientific contribution of this thesis lies in addressing a practical cadastral problem in Palestine through a rigorous geodetic framework. In this study, Jordanian cadastral block sheets are not treated as isolated historical maps requiring a simple transformation. Instead, they are treated as related cadastral units whose geometric relationships must be preserved during the adjustment process.

Moreover, the thesis contributes by applying a simultaneous boundary-conditioned least-squares model to the georeferencing of Jordanian cadastral block sheets in Palestine. This is important because the problem involves not only improving the local fit of a single sheet but also maintaining continuity between adjacent blocks and minimizing inconsistencies along common boundaries.

In practical terms, the results of this research can improve the reliability of cadastral rehabilitation, boundary recovery, subdivision accuracy, and GIS integration. Thus, the contribution of the thesis is both methodological and practical.

1.7 Thesis Scope

This thesis is organized into six chapters. Each chapter addresses a specific part of the research and progressively develops the study from the theoretical and historical background to the development, application, evaluation, and interpretation of the proposed georeferencing approach.

Chapter One introduces the research topic and presents the background of cadastral surveying and historical land settlement in Palestine. It defines the main research problem associated with the positional and geometric inconsistencies between historical Jordanian cadastral block sheets and modern field-survey data. The chapter also presents the research aim and objectives, research questions, general methodology, scope and limitations of the study, and the scientific and practical contribution of the research.

Chapter Two provides the cadastral and land-registration background for the study. It discusses the role of cadastral surveying in land registration and examines the legal, institutional, historical, and spatial aspects of cadastral records, with specific reference to Palestine. Special attention is devoted to historical Jordanian cadastral block sheets, their surveying and mapping characteristics, and the sources of geometric and positional inconsistencies that may arise when these records are combined with modern geospatial data.

Chapter Three provides the theoretical background of georeferencing and coordinate transformation in Geographic Information Systems (GIS). It addresses coordinate reference systems, datums and projections, Ground Control Points (GCPs), Check Points, and the principal transformation models used in the study, including similarity, affine, and polynomial transformations. The chapter also describes least-squares adjustment, residual errors, root-mean-square error (RMSE), and the methods used to assess positional accuracy and geometric consistency between neighboring cadastral blocks.

Chapter Four presents the methodology and the proposed boundary-conditioned least-squares approach developed in this research. Rather than treating each cadastral block as an independent unit, the proposed method considers neighboring blocks as parts of a connected adjustment network. The chapter formulates the mathematical transformation models and condition equations used to connect corresponding tie points and shared-boundary vertices. It also explains the treatment of control points, independent Check Points, Control Tie Points, and withheld Check Tie Points (CTPs), together with the procedures used to compare different transformation models and adjustment scenarios.

Chapter Five discusses the application of the proposed methodology and the results obtained for the Tammun study area. The proposed methodology was applied to six historical Jordanian cadastral blocks: 51, 53, 54, 56, 57, and 58. The chapter describes the preparation of the historical cadastral sheets; the field surveying and identification of reliable control features; the preparation of control- and tie-point datasets; and the implementation of the different transformation and adjustment models. The results are

assessed using residuals, RMSE values, independent Check Points, Control Tie performance, and withheld Check Tie Points. The positional accuracy of individual blocks and the geometric consistency along shared boundaries are evaluated by comparing independent block georeferencing with the simultaneous boundary-conditioned adjustment. The chapter also discusses the practical implications of the results for cadastral reconstruction, GIS integration, and land-administration applications.

Chapter Six presents the conclusions and recommendations of the research. It summarizes the principal findings in relation to the research objectives and evaluates the effectiveness of the proposed boundary-conditioned least-squares approach for improving the georeferencing and inter-block consistency of historical cadastral sheets. The chapter also identifies the main limitations of the study and provides recommendations for future research, wider application of the methodology, and the rehabilitation and integration of historical cadastral records within modern GIS and land-administration systems in Palestine.

CHAPTER 2

LAND REGISTRATION AND CADASTRAL SURVEYING IN PALESTINE

2.1 Introduction

Land administration is the process of recording and administering land rights, restrictions, and responsibilities, as well as land value, land use, and land development. Effective land administration therefore relies on two complementary forms of information: legal and administrative information identifying the rights attached to land, and spatial information locating the land unit to which those interests apply. These two components are closely related in modern land-administration frameworks because a legally recognized interest has limited practical value if the affected parcel cannot be reliably located and maintained in space (Williamson et al., 2010; UN-GGIM, 2020).

Within this broader framework, land registration and cadastral surveying perform different but interdependent functions. Land registration records recognized interests in land, while cadastral surveying provides the geometric description of parcels and boundaries that allows the registered interests to be attached to identifiable spatial units. The International Federation of Surveyors describes the cadastre as a parcel-based land information system that normally contains a geometric description of land parcels linked to records concerning interests in land (FIG, 1995). This relationship is summarized in Figure 2.1.

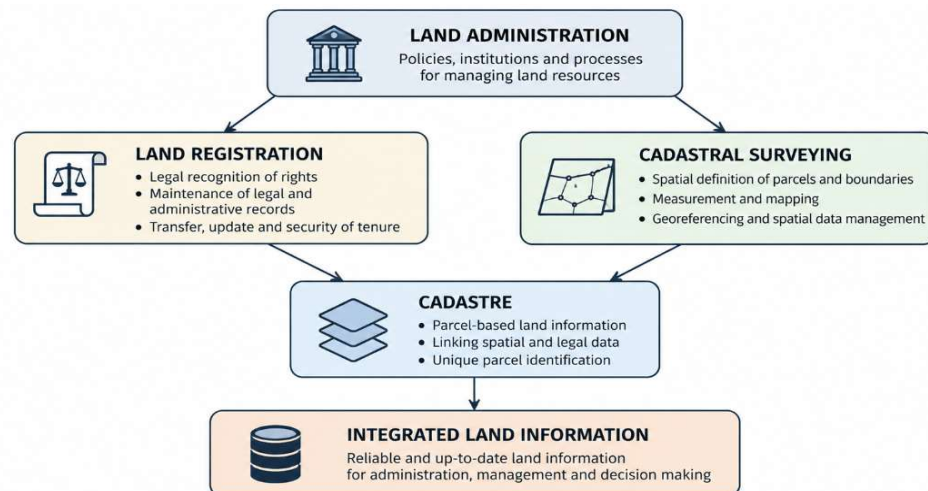


Figure 2.1. Relationship between land administration, land registration, cadastral surveying, and the cadastre.

Source: Prepared by the researcher based on FIG (1995), Williamson et al. (2010), Lemmen et al. (2015), and UN-GGIM (2020).

The distinction between legal and spatial information becomes especially important when historical cadastral records continue to be used within modern surveying and Geographic

Information System (GIS) environments. Many historical cadastral sheets were prepared using conventional field methods, graphical plotting, and paper-based production processes. They may still carry important cadastral information, but their geometry reflects the surveying standards and physical media of an earlier period. Combining such records with present-day coordinate-based data therefore requires an understanding of both their cadastral role and their historical and technical characteristics.

This chapter follows this progression. It first introduces land registration, then explains cadastral surveying and the organization of parcels into cadastral blocks. It subsequently reviews the historical development of cadastral surveying in Palestine, with particular attention to the British Mandate and Jordanian periods because these stages shaped the cadastral framework inherited in the West Bank. The chapter closes by identifying the characteristics of historical Jordanian block sheets that are most relevant to the present research and by establishing the transition to the georeferencing and accuracy concepts discussed in Chapter 3.

2.2 Land Registration

2.2.1 Concept and Purpose

Land registration is the official process by which a competent authority records and updates legally recognized interests in land. These interests vary from one legal system to another and may comprise ownership, leasehold, easements, mortgages, restrictions, public rights, and other duties attached to the land. Its primary aim is to create a systematic, permanent record that underpins tenure security, land transactions, public administration, planning, and dispute resolution.

The objectives of land registration extend far beyond the individual title holder. Reliable land records also provide information for planning, infrastructure, taxation, environmental management, and development, thereby supporting public decision-making. The Voluntary Guidelines on the Responsible Governance of Tenure stress the significance of responsible and transparent governance of tenure, and the Framework for Effective Land Administration considers secure people-to-land relationships central to land-administration reform (FAO, 2012; UN-GGIM, 2020).

However, a land-registration system must be more than a collection of names and legal documents. The registered property must also be spatially identifiable. A written record may include the parcel number, area, owner, or adjoining properties. The cadastral component becomes essential when the precise spatial unit associated with the registered interest must be represented, checked, transferred, or updated. For this reason, the cadastral

map and the land register are not independent records but complementary parts of the same administrative environment.

2.2.2 The Land Register and the Cadastre

The land register primarily contains legal and administrative information, whereas the cadastre organizes the spatial units to which that information relates. The Land Administration Domain Model (LADM) expresses this relationship by distinguishing parties, rights, restrictions and responsibilities, and spatial units. The model is useful conceptually because it separates the legal relationship from the geometry while keeping a formal link between them (Lemmen et al., 2015).

In practical cadastral administration, the parcel is often the basic unit through which this link is maintained. A parcel identifier allows records, survey plans, coordinates, areas, transactions, and other information to refer to the same spatial object. When the geometry of the parcel is changed through subdivision, consolidation, road acquisition, or boundary correction, the corresponding register information must also be maintained consistently. Conversely, a legal transaction should not create ambiguity regarding which spatial parcel is affected.

The principal components of this relationship are summarized in Table 2.1. The table illustrates that no single component is sufficient on its own: the reliability of the system depends on the consistency between legal records, survey information, parcel geometry, and the spatial database used to maintain them.

Table 2.1. Main components of a land registration and cadastral system

Component	Principal Function	Typical Information
Land Registration	Records legally recognized interests in land.	Ownership, rights, restrictions, responsibilities, and transactions.
Land Register	Maintains the legal and administrative record.	Right holder, title information, encumbrances, and registered changes.
Cadastral Parcel	Provides the basic spatial unit of the cadastral system.	Parcel identifier, location, geometry, and area.
Cadastral Survey	Determines or reconstructs parcel geometry.	Boundary evidence, measurements, coordinates, and field records.
Cadastral Map / Plan	Represents cadastral units graphically.	Parcel boundaries, parcel numbers, roads, block limits, and related features.
Spatial Database	Stores and manages digital spatial information.	Geometry, coordinates, attributes, and links to administrative records.

Source: Prepared by the researcher based on FIG (1995), Williamson et al. (2010), and Lemmen et al. (2015).

The institutional value of the cadastre therefore depends heavily on its capacity to maintain correspondence between legal records and spatial reality. Uncertainty or internal inconsistency in the geometry of a registered parcel makes routine activities such as

subdivision, boundary re-establishment, valuation, and comparison of adjacent parcels more difficult. This issue is particularly important in jurisdictions where cadastral evidence still includes old paper maps while new field measurements are acquired in modern digital coordinate systems.

2.3 Cadastral Surveying

2.3.1 Role of Cadastral Surveying

Cadastral surveying is the branch of surveying concerned with the determination, measurement, documentation, and, where legally permissible, re-establishment of land parcels and boundaries. Cadastral surveying is distinguished from general topographic surveying in that cadastral boundaries are the legal or administrative divisions of land. A cadastral boundary may coincide with a physical feature such as a fence, wall, road edge, or cultivation line, but the physical feature and the legal boundary are not necessarily identical. The surveyor must therefore consider both field evidence and official records. A cadastral survey may include the recovery of existing survey monuments, identification of boundary evidence, measurement of distances and angles, determination of coordinates, reconstruction of historical geometry, computation of parcel areas, and preparation or updating of cadastral plans. The specific procedure depends on the law, the status of the boundary, the quality of existing records, and the technology available. Figure 2.2 shows the general workflow from cadastral evidence to an updated cadastral record.

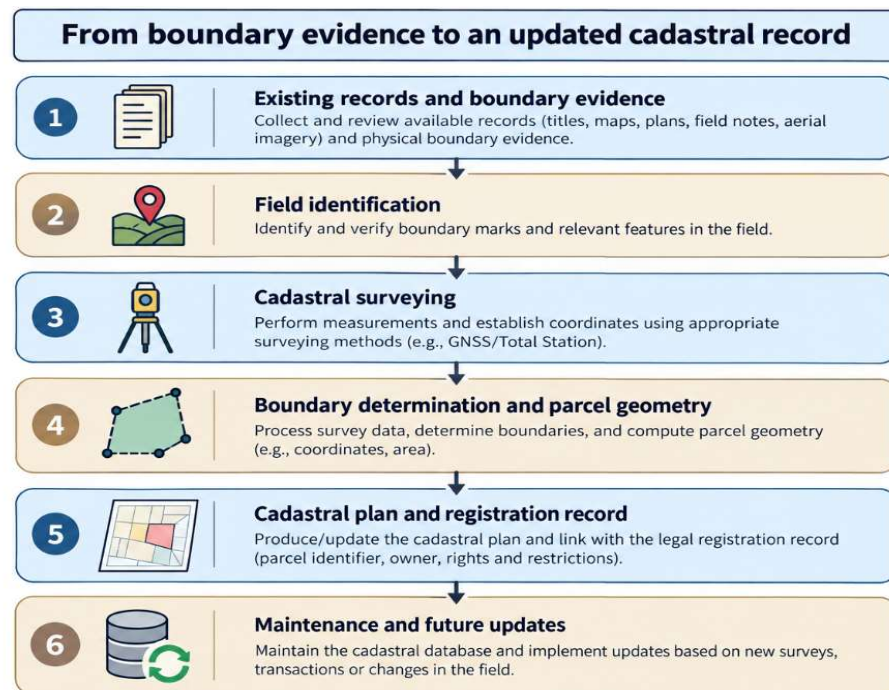


Figure 2.2. General workflow from cadastral evidence to an updated cadastral record.
Source: Prepared by the researcher based on Williamson et al. (2010) and FIG (1995).

Cadastral surveying is therefore both a measurement activity and an evidentiary process. High-precision coordinates are valuable, but the legal significance of a boundary still depends on the validity of the evidence being surveyed. This is an important point in historical-map studies: a modern GNSS observation can provide the present position of an extant monument with great precision, but it does not by itself imply that every line on an old sheet has the same positional accuracy.

2.3.2 Cadastral Surveying and Land Registration as Complementary Functions

Land registration and cadastral surveying are distinct but complementary functions. Registration focuses primarily on who holds a recognized interest and on the nature of that interest, whereas cadastral surveying determines where the corresponding parcel or boundary is located. The two functions are operationally reliable only when the legal and spatial records consistently refer to the same parcel.

Table 2.2 summarizes this distinction. It is useful for understanding the technical issue addressed in this thesis because a historical cadastral sheet may retain documentary and cadastral significance even when its geometric representation requires improvement before integration with modern survey data.

Table 2.2. Functional relationship between land registration and cadastral surveying

Aspect	Land Registration	Cadastral Surveying
Primary Concern	Legal and administrative interests in land	Spatial extent, location, and geometry of cadastral units
Main Question	Who holds what right or interest?	Where is the parcel or boundary located?
Principal Records	Land registers, titles, transactions, and legal documents	Survey observations, field records, coordinates, and cadastral plans
Basic Reference	Registered property and the corresponding right holder	Parcel, boundary line, and boundary point
Main Contribution	Recognition, recording, and maintenance of land rights and interests	Spatial identification, measurement, and re-establishment of land units

Source: Prepared by the researcher based on FIG (1995), Williamson et al. (2010), and Lemmen et al. (2015).

The increasing dependence on digital land-information systems has further reinforced this interdependence. Through overlays, topology checks, and comparison with recent field surveys, the conversion of cadastral plans into digital spatial data may reveal geometric defects that were less apparent on separate paper sheets. Modernization therefore involves more than digitizing old plans; it is a controlled process that accounts for the original quality of the cadastral source and preserves the spatial relationships between neighboring parcels and blocks.

2.4 Cadastral Blocks and the Parcel Framework

2.4.1 Parcels, Blocks, and Block Sheets

In most cadastral systems, land is divided into manageable spatial units to enable parcels to be surveyed, registered, mapped, retrieved, and updated in an orderly manner. Typically, the basic unit of cadastral information is the individual parcel, although groups of parcels may be organized into larger registration or cadastral blocks. The block provides a practical mapping unit. Rather than depicting an entire locality on a single large sheet, parcels are grouped within identifiable map units that can be maintained and referenced separately. A cadastral block sheet (see Figure 2.3) typically depicts the parcel pattern within the block, parcel numbers, and selected cadastral features. Depending on the period and surveying system, it may also include roads, grid marks, survey points, measured distances, annotations, and other information needed to interpret the cadastral record. Figure 2.3 illustrates the conceptual relationship between parcels, cadastral blocks, and a shared block boundary.

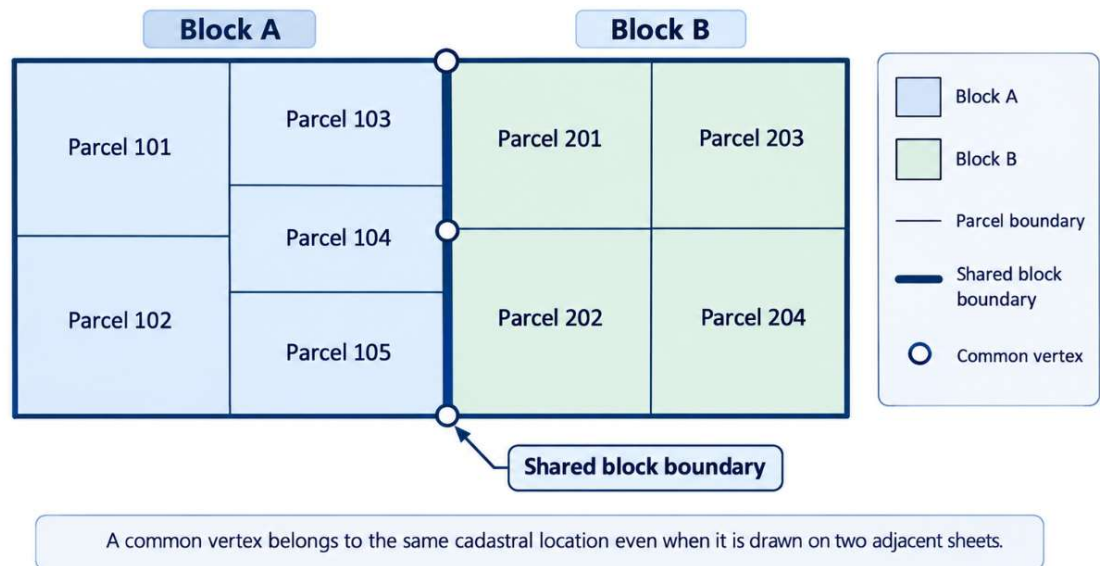


Figure 2.3. Conceptual organization of cadastral blocks, parcels, and a shared block boundary.

Source: Prepared by the researcher.

Parcel boundaries and block boundaries should be clearly distinguished. Parcel boundaries define the individual cadastral units within a block, whereas the block boundary defines the external limit of the block sheet. Where two blocks adjoin, the outer boundary of one block is also the boundary of the adjacent block. Common vertices along this line therefore represent the same cadastral locations, even though they are drawn separately on different paper sheets.

2.4.2 Shared Boundaries and Cadastral Continuity

Adjacent sheets share cadastral boundaries, creating explicit geometric relationships between them. When the same boundary vertex appears on two adjacent block sheets, both

representations should refer to the same physical cadastral point. This relationship can be obscured when old sheets are preserved, copied, scanned, and georeferenced separately because each sheet can contain different local distortions.

In a paper-based environment, small differences at sheet edges may not always be obvious, especially when plans are examined individually. In a GIS environment, however, adjacent sheets can be displayed together, making discrepancies directly visible as gaps, overlaps, or displacements of corresponding boundary vertices. For cadastral purposes, this is more than a cartographic inconvenience because the affected line is a common cadastral boundary.

Table 2.3 summarizes the terminology used in this chapter. Chapter 3 introduces Ground Control Points, independent Check Points, Tie Points, transformation models, and accuracy statistics within the framework of georeferencing and quantitative evaluation. It also provides more detailed definitions of these terms.

Table 2.3. Cadastral terminology used in this chapter

Term	Meaning in the Context of This Thesis
Cadastral Parcel	An identifiable land unit represented and recorded within the cadastral system.
Parcel Boundary	A line defining the cadastral separation between neighboring parcels.
Boundary Point / Vertex	A point forming part of a cadastral boundary and contributing to the geometric definition of a parcel.
Cadastral Block	A spatial unit containing a group of cadastral parcels represented together for surveying and registration purposes.
Cadastral Block Sheet	A map or plan sheet representing parcels and associated cadastral information within a cadastral block.
Shared Block Boundary	A common boundary between two neighboring cadastral blocks that is represented on both block sheets.
Common Boundary Point	A cadastral vertex representing the same cadastral location on adjoining block sheets.

Source: Prepared by the researcher using standard cadastral terminology and the definitions adopted in this thesis.

The concept of the cadastral block is especially important in the present research because the study is not concerned with a single isolated historical map; rather, it deals with a connected set of Jordanian cadastral block sheets. Maintaining the spatial relationship between neighboring sheets is therefore an integral part of the cadastral problem itself, rather than merely a cartographic refinement to be added later.

2.5 Development of Cadastral Surveying in Palestine

The current cadastral situation in Palestine is the product of several historical periods rather than a single continuous surveying system. Successive administrations—particularly the Ottoman, British Mandate, Jordanian, and later Palestinian administrations—developed land records, survey practices, control networks, and map-production methods.

Understanding these stages is necessary because historical cadastral sheets inherit the technical characteristics of the periods in which they were created. Gavish and Kark (1993) characterize the nineteenth and early twentieth centuries as a gradual transition from land registration that was not systematically supported by precise cadastral mapping to a more systematic relationship between registration and statutory maps. The key stages relevant to this thesis are summarized in Figure 2.4.

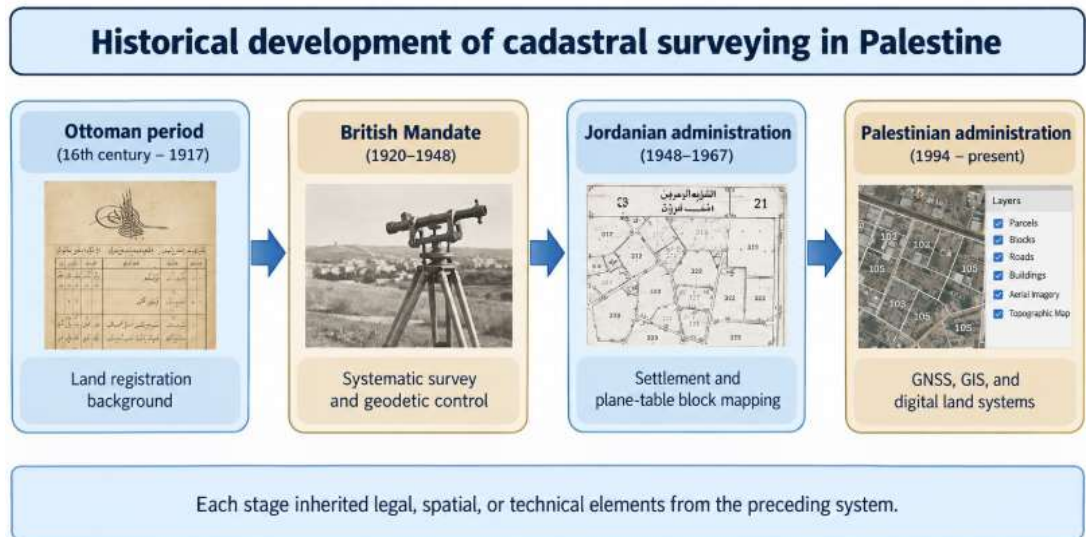


Figure 2.4. Main historical stages in the development of cadastral surveying and land administration in Palestine.

Source: Prepared by the researcher based on Gavish and Kark (1993), Gavish (2005), Tamim and Taha (2016), World Bank (2008), and Younis et al. (2025).

2.5.1 Ottoman Legal and Administrative Background

The Ottoman Land Code of 1858 represented an important step toward formalizing land tenure and registration. Although it established a legal and administrative framework for identifying and recording land, the existence of a land record did not necessarily imply that every registered holding was supported by a cadastral map with precisely defined boundaries. Property boundaries could instead be described using place names, neighboring holdings, local knowledge, written descriptions, or physical features.

As Gavish and Kark (1993) demonstrate, cadastral mapping was introduced gradually in Palestine; it did not emerge fully formed immediately after the land reforms of the nineteenth century. The relevance of the Ottoman period to this thesis is thus primarily institutional and historical: it established a foundation of land-registration practices that later governments developed and modified, whereas the detailed large-scale cadastral mapping on which the present block sheets are primarily based emerged during the twentieth century.

2.5.2 Cadastral Surveying during the British Mandate

The British Mandate period was marked by significant technical developments in surveying and mapping. In 1920, the Department of Surveys was established, and cadastral surveying became much more closely aligned with land-settlement and registration activities. Gavish (2005), for example, provides a useful summary of how the Survey of Palestine was organized around five areas: geodetic control, cadastral surveys, topographic mapping, map production, and support for the land-settlement process itself.

Registration blocks were delineated within villages or registration areas into manageable units and then subdivided into parcels. Parcel boundaries were marked on the ground and surveyed, areas were computed, and the results were drawn on cadastral plans. Tamim and Taha (2016) explain how triangulation and traverse control were used together with traditional field methods within the historical cadastral system. The cadastral plans produced by this system linked land registration to the physical locations of individual properties much more directly than predominantly narrative systems of land description had done.

Figure 2.5 illustrates the logic of the cadastral mapping framework. No single historical map is reproduced here; rather, the figure is a schematic summary of how geodetic control, field surveys, registration blocks, and parcels were integrated to produce the final paper cadastral plan.

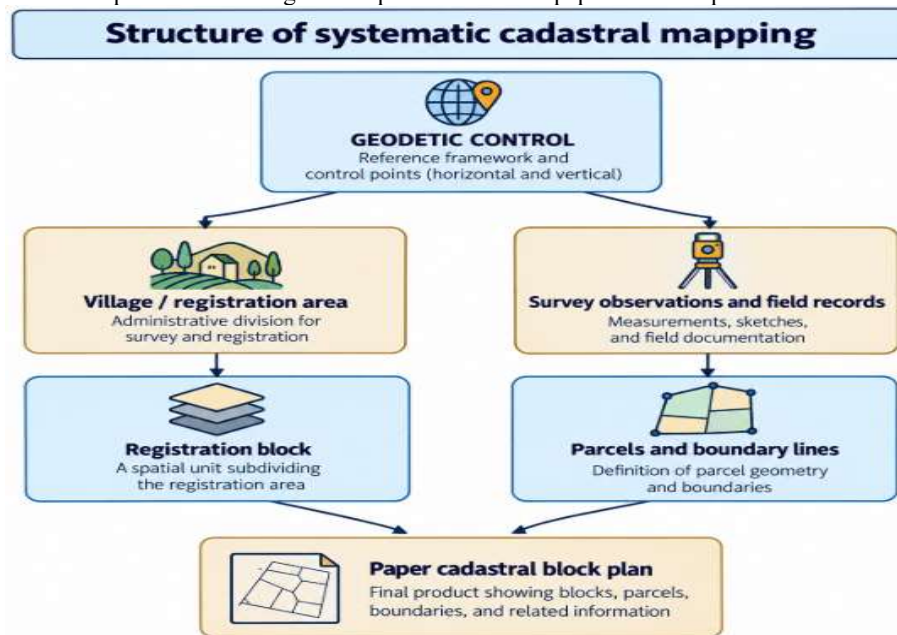


Figure 2.5. Schematic structure of systematic cadastral mapping developed during the twentieth-century cadastral framework.

Source: Prepared by the researcher based on Gavish (2005) and Tamim and Taha (2016).

The British surveying system is relevant to this thesis because later cadastral systems implemented in the West Bank adopted key elements of its design, including geodetic control, registration blocks, parcel numbering, and paper cadastral plans. The historical

coordinate systems established during this period also persisted in later cadastral and mapping activities. This context is important because current geodetic modernization efforts in Palestine must account for legacy reference systems (Younis et al., 2025).

2.5.3 Cadastral Surveying during the Jordanian Period

The Jordanian period (Fig. 2.3) is the era most closely associated with the dataset examined in this thesis. Land settlement and cadastral survey work continued after the transfer of authority in 1948 under the auspices of Jordanian land and survey agencies. Earlier cadastral concepts were refined rather than replaced by an entirely new system of land subdivision.

Tamim and Taha (2016) state that the existing geodetic control was strengthened during the Jordanian period and that plane-table surveys were conducted to measure parcel geometry. Direct tape measurements were also recorded, and coordinate grid-line marks were plotted on many cadastral maps at approximately 500 m intervals in both coordinate directions. This information remains useful because it helps explain how these paper sheets were compiled and what reference information may still be preserved within them.

Essentially, the Jordanian cadastral block sheet was a graphical representation on paper. Boundaries, lot characteristics, streets, grid points, survey details, notes, and other information were drawn directly on the sheet. Accordingly, the geometry preserved in a modern scan reflects not only the original field measurements but also plotting precision, line weight, paper distortion, reproduction artifacts, and subsequent digitization errors.

Tamim and Taha (2016) note that historical cadastral sheets in the West Bank were produced at scales ranging from approximately 1:625 to 1:10,000 and report that neighboring sheets often do not align well, producing gaps and overlaps when adjacent maps are overlaid directly. This is particularly relevant to the present research because it concerns an entire network of adjacent Jordanian block sheets rather than the accuracy of a single independent map.

The major attributes of such historical block sheets and their implications for use today are highlighted in Table 2.4.

Table 2.4. Characteristics of Jordanian cadastral block sheets relevant to modern spatial use

Historical characteristic	Implication for present-day use
Conventional terrestrial field surveying	Original boundary positions reflect the accuracy attainable with historical observations and control.
Plane-table parcel measurement	A substantial part of the parcel geometry was represented through graphical field and plotting procedures.
Paper-based block plans	The sheet can undergo physical deformation during storage and repeated use.

Historical characteristic	Implication for present-day use
Grid marks on many sheets	Grid information can assist interpretation and spatial referencing of the sheet.
Selected tape-measured distances	Historical measurements may provide supplementary evidence for interpreting the original survey.
Manual graphical drafting	Line thickness and plotting precision impose a limit on recoverable position from the drawing.
Copies and scanned images	Reproduction and scanning can add further scale or local geometric effects.
Separate sheets for adjoining blocks	Neighboring blocks may not coincide when treated independently in a digital environment.

Source: Prepared by the researcher based primarily on Tamim and Taha (2016).

The final characteristic listed in Table 2.4 is central to the argument of this thesis. When two block sheets adjoin and share a common boundary or vertex, the cadastral relationship extends across the sheet edge. If the sheets are subsequently transformed independently, there is no guarantee that both representations of the same boundary point will coincide spatially. The historical tiling of the cadastre therefore creates a modern integration problem when sheets are treated individually.

2.5.4 Cadastral Surveying under the Palestinian Administration

Under the Palestinian administration, land registration has shifted toward more formalized procedures, electronic data management, contemporary surveying equipment, GIS, and the adoption of geographic coordinate systems as the basis for spatial databases. Consequently, land-registration bodies have had to manage new survey inputs while also maintaining a substantial body of historical cadastral data.

Internationally supported land-administration programs have emphasized systematic land surveying and registration together with institutional strengthening and modernization of the Palestinian Land Authority. The Second Land Administration Project, approved in 2008, explicitly supported systematic land surveying and registration as well as institutional development and modernization of land-administration services (World Bank, 2008). A later Real Estate Registration Project continued the emphasis on property registration and the automation of land-related services (World Bank, 2019).

One example of a recent technical development is the Palestinian Geodetic Reference Frame (PAL-GRF2023). Younis et al. (2025) established “a new GNSS compatible reference frame tied to ITRF2020 and transformation parameters between the new reference frame and legacy datums such as PAL1923.” This development is important for cadastral modernization because reliable integration of legacy and contemporary spatial datasets requires a common reference framework.

Figure 2.6 illustrates the transition from historical paper plans to a modern digital spatial environment. As the figure indicates, scanning old plans is not the final step in data modernization. The resulting raster must

still be interpreted and linked to authoritative modern reference data before it can be used reliably in GIS and digital land administration.

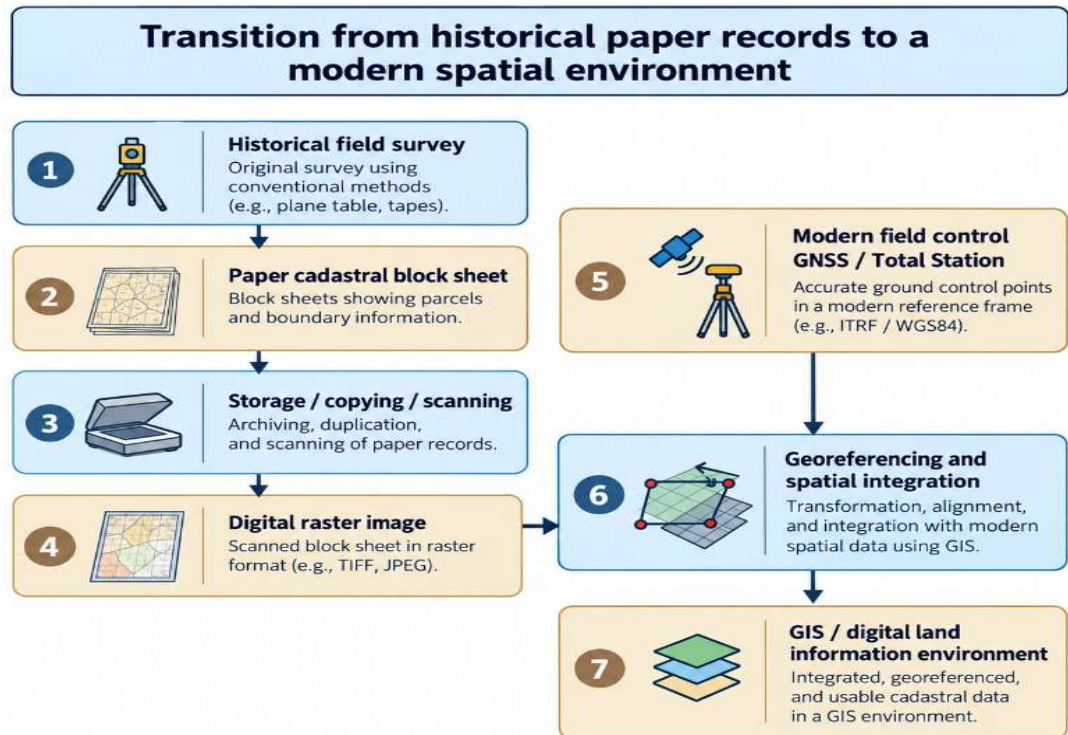


Figure 2.6. Transition from historical paper cadastral records to a modern digital spatial environment.
Source: Prepared by the researcher based on World Bank (2008), Tamim and Taha (2016), and Younis et al. (2025).

2.5.5 Comparison of the Main Historical Periods

The preceding periods should not be viewed as entirely separate eras with rigid cutoff points. Successive governments inherited laws, survey practices, control information, and mapping conventions from earlier administrations. As a result, a single cadastral case today may combine a GNSS observation from 2010, coordinates expressed in a historical system, a Jordanian paper block sheet, and an electronic parcel database.

Table 2.5 summarizes the main contribution of each period and its relevance to the cadastral problem examined in this thesis.

Table 2.5. General development of cadastral surveying and land administration in Palestine

Period	Main development	Surveying / mapping environment	Relevance to this thesis
Ottoman period	Formalization of land-tenure and registration practices	Primarily documentary records; limited systematic modern cadastral mapping	Provides the legal and administrative background inherited by later systems.
British Mandate	Systematic survey organization, geodetic control, land settlement, cadastral blocks, and parcels	Triangulation, traverse, conventional field surveying, and paper plans	Established much of the technical cadastral framework inherited by later systems.

Period	Main development	Surveying / mapping environment	Relevance to this thesis
Jordanian administration	Continuation and expansion of settlement and cadastral block mapping in the West Bank	Densified control, plane-table surveying, tape measurements, and paper block sheets	Direct origin of the historical block sheets investigated in this research.
Palestinian administration	Systematic registration and modernization of land information	GNSS, total stations, GIS, digital databases, and modern reference-frame development	Provides the current environment in which historical maps must be integrated.

Source: Prepared by the researcher based on Gavish and Kark (1993), Gavish (2005), Tamim and Taha (2016), World Bank (2008), and Younis et al. (2025).

2.6 Historical Jordanian Block Sheets and Their Relevance to the Present Research

2.6.1 Geometric Characteristics of Historical Paper Sheets

Scanned historical cadastral block sheets reflect multiple stages of geometric uncertainty. Each boundary point represented on a sheet passed through several stages: field survey, plotting on paper, storage, possible copying and scanning, and, ultimately, digitization using modern software. The fact that the final product is a digital image does not mean that it has the same inherent geometric quality as a cadastral dataset generated directly from modern coordinate files.

Figure 2.7 provides a conceptual representation of the processing stages applied to historical cadastral datasets. Although the figure does not assign a specific error magnitude to each stage—because the magnitude varies from sheet to sheet—it demonstrates that a discrepancy observed in GIS may result from multiple sources and that the transformation itself is not necessarily responsible for all residual differences.

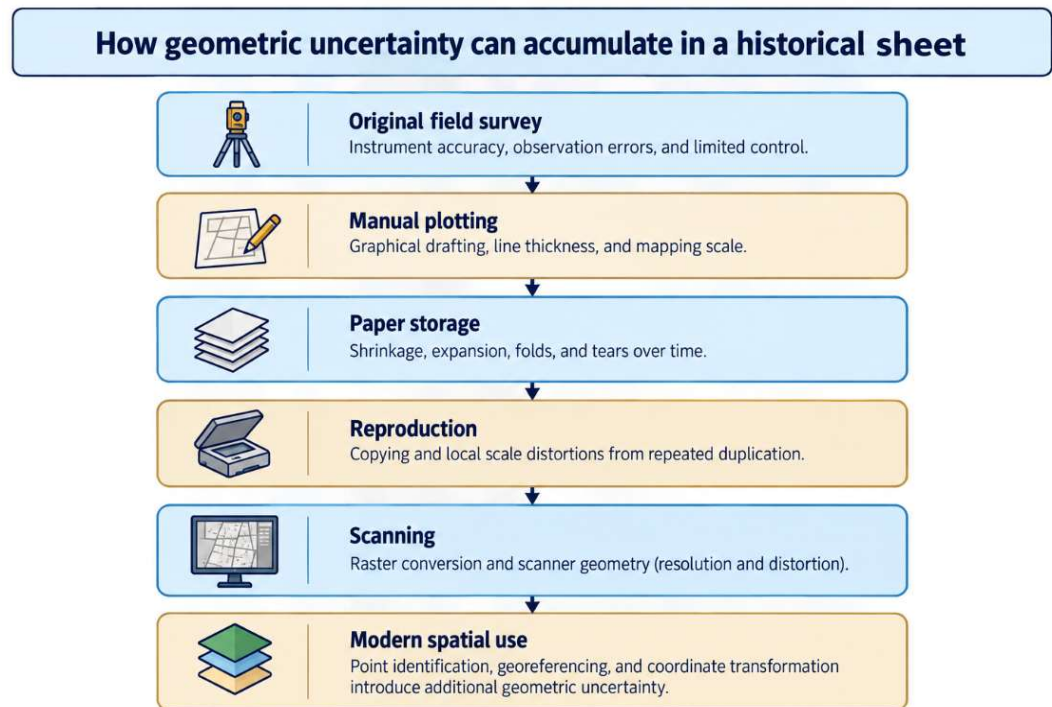


Figure 2.7. Conceptual accumulation of geometric uncertainty from the historical survey to modern digital use.

Source: Prepared by the researcher based on Bitelli and Gatta (2011), Brovelli and Minghini (2012), Havlíček and Cajthaml (2014), and Tamim and Taha (2016).

One clear example of an intrinsic graphical limitation is map scale. According to Tamim and Taha (2016), a line width of approximately 0.2 mm on a 1:2500 cadastral map corresponds to about 0.50 m on the ground. This does not mean that every point on such a map has an error of 0.50 m; rather, it illustrates the order of magnitude represented by a very small graphical displacement on a large-scale paper map. This is an important consideration when historical linework is compared with modern GNSS coordinates measured to centimeter-level precision.

Physical deterioration can introduce additional variability. Over decades of storage and use, paper can expand, contract, fold, tear, or stretch. Bitelli and Gatta (2011), together with other studies of historical maps, demonstrate that map deformation is an important consideration when georeferencing old cadastral documents. Its effect may be systematic across much of a sheet or localized around damaged areas; consequently, the behavior of a historical map is not necessarily uniform.

Copying and scanning must also be considered part of the map's history. Linework may appear visually sharp in a high-resolution raster, but visual sharpness does not restore the positional accuracy of the original drawing. A scanned file preserves the geometry of the source document while potentially introducing additional distortions through reproduction, sheet placement, or the scanning process itself. Tamim and Taha (2016) measured discrepancies in scanned Jordanian cadastral maps and confirmed the need to distinguish digital-image resolution from spatial accuracy.

2.6.2 Adjoining Sheets, Gaps, and Overlaps

This issue is compounded when multiple historical sheets are expected to form a single unified cadastral fabric. Although processing each sheet independently can improve its fit to selected control information, discrepancies may remain along shared boundaries with adjacent sheets. This concern is especially important in cadastral mapping, where a sheet edge may coincide with a legally significant block boundary rather than an arbitrary cartographic break.

Tamim and Taha (2016) explicitly report problems with the relative accuracy of adjoining Jordanian cadastral sheets in the West Bank, including gaps and overlaps when neighboring sheets are joined. Similar multi-sheet issues have been discussed in the broader historical-map literature. Cajthaml (2013) proposed a global adjustment in which the transformation parameters of neighboring map sheets are estimated under continuity conditions along

common borders. Janata and Cajthaml (2021) subsequently formalized this approach as a constrained least-squares formulation to improve adjacency in multi-sheet maps.

Figure 2.8 illustrates the cadastral implication of this problem. When the same shared boundary point is represented on two sheets that are treated independently, two distinct digital positions may result. A boundary-connected treatment recognizes that the two representations correspond to a single cadastral location and should therefore be considered simultaneously during adjustment.

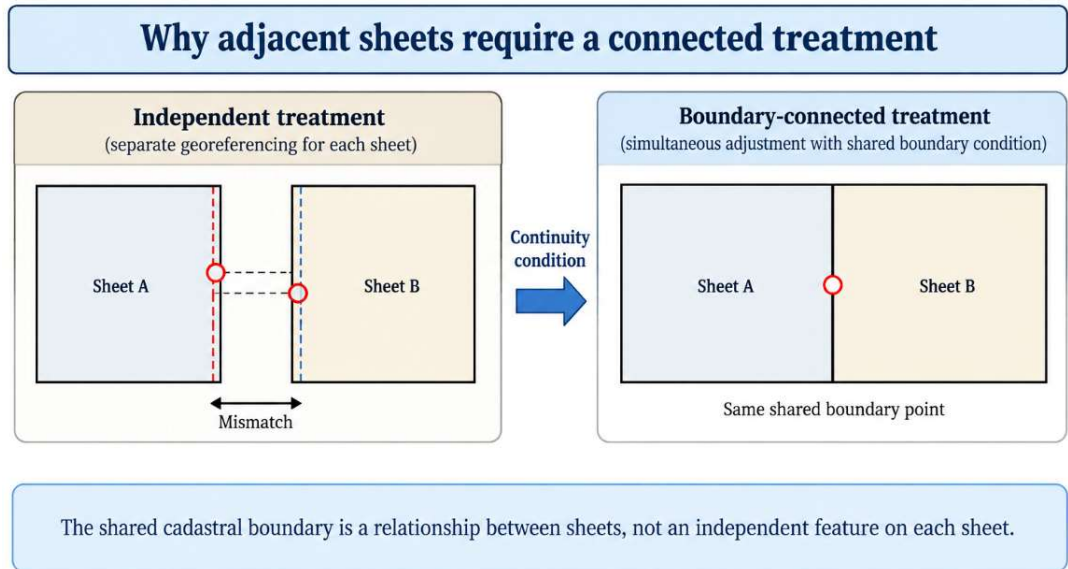


Figure 2.8. Conceptual difference between independent treatment of adjacent sheets and a boundary-connected treatment.

Source: Prepared by the researcher based on Cajthaml (2013), Janata and Cajthaml (2021), and the cadastral context of this thesis.

This relationship should be distinguished from ordinary positional control. External control defines the relationship between a historical map and the target coordinate system, whereas the common cadastral boundary connects neighboring sheets to one another. Both are important, but they address different questions: the former concerns absolute positioning, while the latter concerns the internal continuity of the cadastral fabric.

2.6.3 Relevance to the Tammun Cadastral Blocks

The six adjacent historical Jordanian cadastral blocks used in the applied portion of this thesis are Tammun Blocks 51, 53, 54, 56, 57, and 58. They are treated as a single cadastral group of adjoining sheets rather than as six isolated maps. Their common boundaries provide a practical framework for comparing the accuracy of conventional independent georeferencing with that of a solution that incorporates common-boundary constraints.

Accordingly, this research does not attempt to redefine the legal cadastre or replace historical source documents. Its technical goal is to improve the spatial integration of scanned block sheets while retaining their relationship to trusted modern control observations and minimizing inconsistencies along common boundaries. Chapter 3

introduces the terminology and theory of georeferencing, including affine and polynomial transformation models, Ground Control Points and independent Check Points, RMSE, and the evaluation of Tie Points. The Boundary-Conditioned Least-Squares Approach (Boundary-LSA) and the mathematical equations defining the proposed solution are presented in Chapter 4.

The issues summarized in Table 2.6 inform the subsequent analysis. They generally describe practical limitations encountered when visually aligning historical cadastral blocks.

Table 2.6. Historical-sheet issues and their implications for the present research

Issue Identified in the Historical Cadastral Material	Implication for This Research
Historical terrestrial survey and control limitations	Modern observations may be more precise than the spatial information recoverable from the original map.
Graphical plotting at fixed map scales	Small drawing displacements may represent substantial distances on the ground.
Paper aging and local deformation	The sheet may contain non-uniform geometric distortions affecting positional reliability.
Copies and scanned raster images	Digitization preserves inherited distortions and may introduce additional geometric effects.
Separate historical sheets for adjoining blocks	Independent georeferencing may result in gaps, overlaps, or displaced common vertices between neighboring blocks.
Shared cadastral boundaries and points	Neighboring sheets contain geometric relationships that can be used to evaluate and improve boundary continuity.
Modern GNSS/GIS environment	A consistent reference framework enables historical cadastral information to be compared and integrated with present-day spatial data.

Source: Prepared by the researcher based on Tamim and Taha (2016), Cajthaml (2013), Janata and Cajthaml (2021), and Younis et al. (2025).

2.7 Summary

This chapter provided the cadastral and historical background required for the remainder of the thesis. Land registration was introduced as the legal and administrative component responsible for recording recognized interests in land, while cadastral surveying was presented as the spatial component for identifying, measuring, representing, and maintaining parcels and boundaries. The cadastre links these components through spatial parcel information.

The chapter also described the role of cadastral blocks and block sheets. Blocks are mapped as separate units, but their boundaries are not necessarily independent. Adjacent blocks may share the same cadastral locations along boundary lines and at common vertices. This relationship is important when historical paper sheets are transformed into a common digital environment because separate treatment may result in geometric discontinuities along shared edges.

The historical review showed that land administration in Palestine evolved through successive stages. The Ottoman period provided an important legal and administrative basis for systematic land registration. The British Mandate introduced a more structured surveying system based on geodetic control, registration blocks, parcel surveys, and cadastral plans. During the Jordanian administration of the West Bank, cadastral settlement and mapping continued using conventional field and graphical methods, producing the type of paper block sheets that constitute the core historical material analyzed in this research. Palestinian land administration has gradually incorporated systematic registration, GNSS, total stations, GIS, digital databases, and a modern geodetic reference framework. These technological developments enable better integration of historical cadastral information, but they do not eliminate the geometric limitations inherited from the old sheets. The position of a digitized historical boundary can be influenced by survey uncertainty, graphical plotting, map scale, paper deformation, reproduction, and scanning. Of particular importance to the present study is the well-documented poor relative agreement between some adjacent Jordanian cadastral sheets, which may appear as gaps and overlaps when neighboring maps are juxtaposed. The six selected Tammun blocks—51, 53, 54, 56, 57, and 58—therefore provide a connected cadastral setting in which both individual positional performance and inter-block continuity must be considered. This background forms the basis for Chapter 3, which presents the georeferencing principles, transformation models, control and check points, accuracy measures, and Tie Point concepts required for the quantitative analysis.

Chapter 3

Georeferencing in GIS and Transformation Models

3.1 Introduction

Georeferencing is one of the fundamental operations performed in GIS. Historical maps cannot simply be scanned and overlaid on a current base map without first being referenced to a suitable coordinate system. A historical map is a spatial document created within a particular surveying tradition, reference frame, drawing scale, and cartographic practice. Introducing such maps into a modern GIS environment therefore requires a carefully controlled transformation procedure. This is particularly important in cadastral applications, where even small positional discrepancies may affect the representation of parcel boundaries, registered areas, and the interpretation of land rights (Sengupta et al., 2016).

Jordanian settlement maps in Palestine provide a clear example. These maps were produced under different technical conditions and often in historical or local coordinate systems, whereas recent geospatial datasets are commonly based on precise GNSS observations and modern reference frames. Misalignment becomes evident when the datasets are overlaid without appropriate preprocessing and may appear as positional offsets, rotation, or nonuniform distortion of parcel geometry. Georeferencing must therefore precede reliable interpretation of the historical sheets in relation to recent spatial datasets (Forejt et al., 2020).

The problem is not caused solely by the transformation between historical and modern coordinate systems. The physical condition and handling history of the paper on which each cadastral sheet was drawn constitute another important source of distortion in older cadastral records. Storage, repeated handling, humidity, temperature changes, folding, scanning, and aging can all alter a sheet subtly over time, causing stretching, shrinkage, bending, or other local displacements. Such distortion is rarely uniform: some parts of a sheet may preserve their original geometry relatively well, while others are more strongly affected. Consequently, a single simple transformation may not always be sufficient to represent the observed deformation (Forejt et al., 2020).

Georeferencing in GIS and Transformation Models

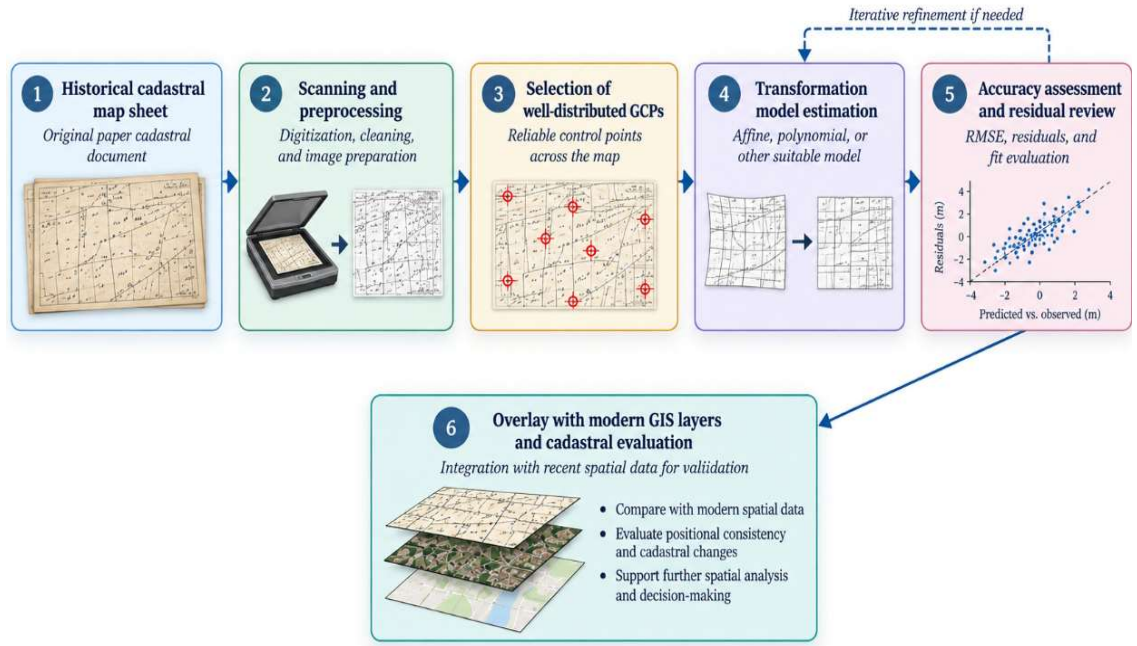


Figure 3.1. General workflow of georeferencing historical cadastral maps.

Source: Prepared by the researcher.

Mathematically, georeferencing establishes a relationship between the coordinates measured or digitized on the historical map and the coordinates of the target reference system. Its general form is given in Equation (3.1) (Luft and Schiewe, 2021; Tamim and Taha, 2016):

$$X = f(x, y), \quad Y = g(x, y) \quad (3.1)$$

where (x, y) are coordinates in the historical source map, (x', y') are the coordinates in the target reference system, and f and g are functions defining the transformation from one system to the other.

The reliability of this relationship depends primarily on the GCPs used to estimate it. GCPs should be easily recognizable on the historical map and must have known, reliable coordinates in the target system. Their effectiveness is not determined by quantity alone. The quality, stability, and spatial distribution of control points are equally important. A transformation that is well defined by points located near one another on the sheet can have an acceptably low overall RMSE and still have large local errors near the edges of the sheet or in areas that are weakly controlled by selected GCPs. For this reason, the selection of GCPs is perhaps the most critical judgment made during the georeferencing process (Bozzano et al., 2024).

Georeferencing historical cadastral sheets should not be regarded merely as a visualization task in cadastral applications. Helmert, affine, projective, and polynomial models can reduce some forms of displacement or deformation; however, these transformation models

cannot eliminate all local misfits within cadastral sheets. Residual errors may persist along parcel boundaries or between adjacent blocks and may propagate directly into the cadastral fabric. Therefore, georeferencing quality should be assessed using both numerical indicators and the spatial behavior of parcel geometry (Younis, 2015).

Least-squares adjustment formalizes this process when more observations are available than are strictly required to determine a solution. Rather than forcing the transformed geometry to pass exactly through a minimum set of points, the least-squares method considers all available observations and determines the solution that minimizes the sum of squared residuals. This makes the method suitable for geodetic and cadastral networks in which observations contain random errors and the solution should represent the dataset as a whole rather than depend on a small selected subset of points (Ghilani and Wolf, 2012).

In the present research, georeferencing is considered the initial spatial step in reconstructing the Jordanian cadastral block sheets within a modern reference system. However, it is not treated as the final solution. The study also addresses gaps, overlaps, and inconsistencies between adjacent cadastral blocks. For that reason, conventional georeferencing is followed by a boundary-conditioned least-squares adjustment, through which neighboring sheets are connected by tie points and shared-boundary conditions within a single mathematical framework (Younis, 2015).

Chapter 3 therefore sets out the theory required for the later methodological stages of this thesis. Topics include coordinate systems and geodetic datums, control points and their use, transformation models, least-squares adjustment, accuracy assessment, sources of error and georeferencing quality, and the integration of georeferenced data into GIS. These topics are considered within the broader objective of reconstructing historical cadastral data with improved positional accuracy and spatial consistency (Sengupta et al., 2016).

3.2 Coordinate Systems and Geodetic Datums

Coordinate systems and geodetic datums form the spatial language through which GIS datasets are located, compared, and measured. A dataset may contain accurate geometry, but that geometry cannot be interpreted correctly unless its reference framework is known. This issue becomes particularly important when the data come from different periods or institutions. Two datasets may appear similar in shape, yet fail to coincide when overlaid because they are based on different datums, projections, or measurement conventions (Younis, 2020).

Coordinate systems provide the mathematical framework used to describe the position of points on or near the Earth's surface. In Geographic Information Systems (GIS), coordinate reference systems are generally classified into Geographic Coordinate Systems (GCS) and Projected Coordinate Systems (PCS). A GCS represents positions using angular coordinates, mainly latitude and longitude, referenced to an ellipsoidal approximation of the Earth. Although geographic coordinates are suitable for regional and global applications, projected coordinates are generally more convenient for cadastral and engineering work because distances, areas, offsets, and parcel-boundary relationships are normally calculated in linear units such as meters (Longley et al., 2015).

An important component of a geographic coordinate system is the reference ellipsoid, which provides a smooth mathematical approximation of the irregular shape of the Earth. Ellipsoids are principally defined by their semi-major axis and flattening, and different reference systems may employ different ellipsoids depending on the geographical region and the period in which the geodetic network was established (Hofmann-Wellenhof and Moritz, 2006). Historical mapping systems commonly used regional ellipsoids such as the Clarke 1880 family, whereas modern geocentric systems are associated with ellipsoids such as GRS80 and WGS84. This distinction is important when historical cadastral data are combined with modern GNSS observations because coordinates derived from different reference systems cannot automatically be considered equivalent.

Projected coordinate systems transform positions from the curved ellipsoidal surface onto a two-dimensional plane using a mathematical map projection. The resulting coordinates are commonly expressed as Easting (E) and Northing (N) in meters. No map projection can preserve shape, area, distance, and direction simultaneously; therefore, some distortion is unavoidable and the projection must be selected according to the location, extent, and intended application of the spatial data (Snyder, 1987). Common projections include Transverse Mercator (TM), Universal Transverse Mercator (UTM), and Cassini–Soldner. The relationship between the ellipsoid, map projection, and datum is summarized in Figure 3.2.

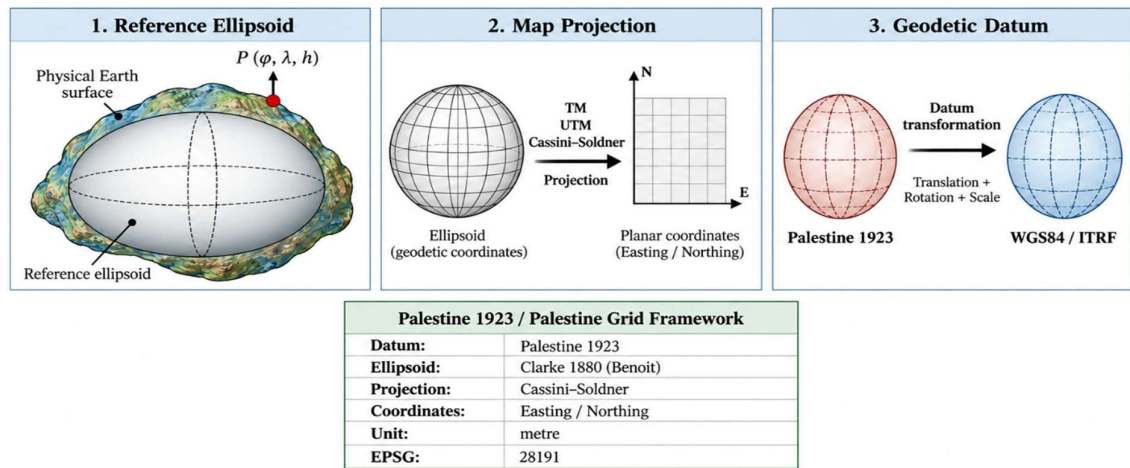


Figure 3.2. Conceptual relationship between the reference ellipsoid, map projection, geodetic datum, and the Palestine 1923 / Palestine Grid reference framework.

Source: Prepared by the researcher based on Hofmann-Wellenhof and Moritz (2006), Snyder (1987), and the EPSG Geodetic Parameter Dataset (IOGP, 2026).

A geodetic datum defines how the reference ellipsoid is positioned and oriented relative to the Earth. Consequently, the same physical point may have different coordinate values when expressed in different datums (Ghilani, 2017). Traditional datums were commonly designed to provide a good regional fit, whereas modern systems such as WGS84 and ITRF are geocentric and referenced to the Earth's center of mass. Of particular relevance to this research is the Palestine 1923 / Palestine Grid (EPSG:28191), which is based on the Palestine 1923 datum, the Clarke 1880 (Benoit) ellipsoid, and the Cassini-Soldner projection, with coordinates expressed as Easting and Northing in meters (IOGP, 2026). When datasets referenced to different datums are integrated, an appropriate datum transformation is required. Such transformations may involve translation, rotation, and scale parameters, as in Helmert-type transformations (Ghilani, 2017). This issue is particularly important in the present research because historical Jordanian cadastral block sheets are integrated with modern surveying and GNSS observations. Correct identification of the coordinate system, ellipsoid, projection, and datum is therefore necessary before evaluating georeferencing accuracy; otherwise, systematic reference-system differences may be incorrectly interpreted as map deformation or transformation error.

The selected coordinate system and datum also affect calculations performed with a dataset. The reference framework influences the computation of parcel areas, boundary lengths, spatial overlays, proximity analyses, and other derived measurements. Using an unsuitable framework, or combining datasets without accounting for reference-system differences, can propagate systematic errors into subsequent computations. The final map

may appear visually consistent while the measurements on which it is based remain biased (Longley et al., 2015; Younis, 2020).

Historical cadastral maps require particular caution in this respect. Before georeferencing begins, the researcher must identify, as far as possible, the original system in which the map was produced and the modern system into which it will be transformed. Misunderstanding the original reference framework may cause the transformation model to compensate for differences that are not geometric distortions but reference-system inconsistencies. In such cases, the transformation may reduce one visible mismatch while introducing another, less obvious error into the dataset (Forejt et al., 2020).

In this study, coordinate systems and geodetic datums are not treated merely as background definitions; they form part of the basis for reconstructing the Jordanian cadastral sheets. Meaningful results require a clearly defined reference framework before transformation, least-squares adjustment, and GIS-based evaluation are undertaken. This is particularly important in cadastral research, where the reliability of the final product depends on both positional accuracy and preservation of boundary relationships (Longley et al., 2015; Younis, 2020).

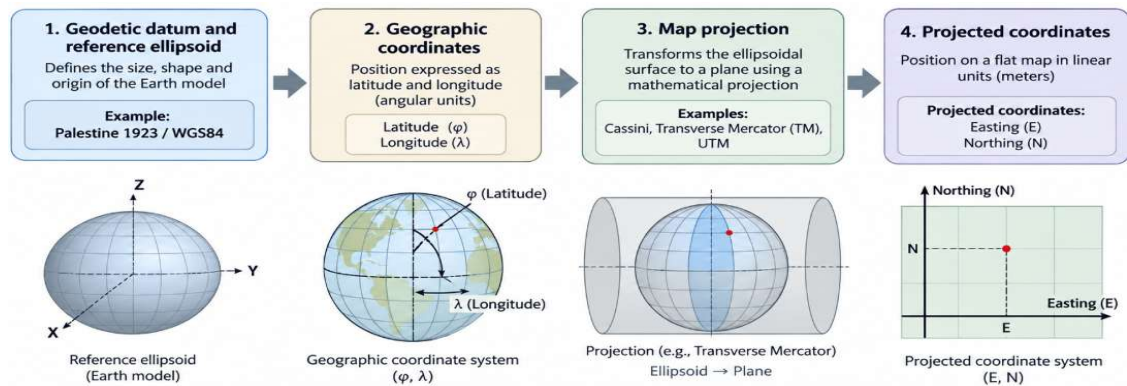


Figure 3.3. Relationship between geodetic datum, geographic coordinates, map projection, and projected coordinates.

Source: Prepared by the researcher based on Longley et al. (2015) and Younis (2020).

3.3 Ground Control Points (GCPs)

Ground Control Points provide the practical link between the historical map and the modern coordinate system. Through these points, the transformation model receives the information needed to relate historical map coordinates to present-day coordinates. Consequently, georeferencing quality depends strongly on the selected points, including their ease of identification, stability on the ground, coordinate accuracy, and spatial distribution across the map sheet (Bozzano et al., 2024).

A GCP is a point that can be identified in both the source and target datasets. In this research, it may be a feature represented on a Jordanian cadastral sheet that is also identifiable in modern data or through field observation. The corresponding coordinate pair is used as an observation to estimate the transformation parameters after the same physical point has been identified in both systems. This seemingly simple requirement is critical because any point-identification error directly affects the transformation model (Ghilani and Wolf, 2012).

Control points should be stable, unambiguous, and clearly identifiable. Examples in cadastral and surveying work include road intersections, fixed parcel corners, permanent building corners, survey marks, stone walls, and other features that have remained unchanged over time. The essential requirement is not only that a feature appears on the historical map, but also that the researcher can confidently identify the same feature in the target reference framework. An uncertain point can be more harmful than useful, even if its inclusion increases the number of available control points (Forejt et al., 2020).

Point quality is as important as spatial distribution. A transformation based on well-distributed GCPs is generally better able to represent sheet deformation across the mapped area. In contrast, a cluster of control points in one part of the map may produce strong local agreement near that cluster but poorer performance elsewhere. This is particularly problematic near map edges, corners, and shared cadastral boundaries. A low RMSE can therefore mask local distortions that become apparent only through detailed examination of the parcel geometry (Bozzano et al., 2024).

The minimum number of Ground Control Points (GCPs) required depends on the transformation model and the number of unknown parameters to be estimated. For a two-dimensional polynomial transformation of order m , the minimum number of GCPs required can be determined from the number of polynomial terms as:

$$N_{min} = \frac{(m + 1)(m + 2)}{2} \quad (3.5)$$

where N_{min} is the minimum number of GCPs required and m is the order of the polynomial transformation. Accordingly, a first-order polynomial transformation, which corresponds to the two-dimensional affine model, requires a minimum of three GCPs. A second-order polynomial transformation requires at least six GCPs, while a third-order polynomial transformation requires at least ten GCPs.

These values represent only the mathematical minimum needed to determine the transformation parameters. In practical georeferencing, using only the minimum number of control points is generally not recommended. Additional reliable and well-distributed

GCPs provide redundancy and allow the transformation parameters to be estimated through an overdetermined least-squares solution. This improves the stability of the transformation and enables the residuals to be evaluated so that weak or inconsistent observations can be identified (Ghilani and Wolf, 2012).

Accordingly, the number of GCPs selected should exceed the mathematical minimum whenever reliable observations are available, while maintaining good spatial distribution across the sheet. This redundancy supports both stable parameter estimation and meaningful residual-based quality control (Ghilani and Wolf, 2012).

More control points do not necessarily improve every transformation. If additional points are poorly identified, poorly measured, or clustered in unfavorable locations, they may degrade the solution rather than improve it. Therefore, GCP selection should be based on both numerical criteria and professional judgment. In general, a smaller number of reliable, well-distributed points is preferable to a larger number of uncertain observations (Forejt et al., 2020).

The positional accuracy of control points also requires careful attention. Any error in a GCP is incorporated into the transformation model and propagated to the transformed coordinates. The error therefore does not remain confined to a single point; it influences the estimated parameters and, through them, the entire transformed sheet. GNSS and total-station observations are commonly used in modern cadastral applications to establish or verify control coordinates because of their accuracy in boundary-sensitive work (Younis, 2015).

After a transformation is estimated, residual analysis provides an important means of checking the behavior of the selected points. A residual represents the difference between the observed coordinate of a point and its coordinate as computed by the transformation model. If one point has a much larger residual than the others, it should not be removed automatically, but it must be investigated. The cause may be a measurement error, a mistaken identification, a local map distortion, or an unsuitable transformation model (Mikhail et al., 2001).

In cadastral applications, the importance of GCPs extends beyond the transformation statistics. Control points influence the position of parcel boundaries and the fit between neighboring parcels and blocks. An error in a control point can create a boundary displacement, produce a local overlap, or disturb the continuity of a shared line. Selecting GCPs therefore requires both technical accuracy and a careful understanding of the cadastral features represented on the historical map (Sengupta et al., 2016).

In this thesis, GCPs are regarded as one of the principal factors affecting georeferencing quality. They are not merely locations used to establish coordinate pairs; they influence the reliability of the transformation, the interpretation of residuals, and the success of subsequent adjustment stages. A weak control network propagates uncertainty into later stages, whereas a strong control network provides a sound basis for reconstructing historical cadastral sheets (Mikhail et al., 2001; Bozzano et al., 2024).

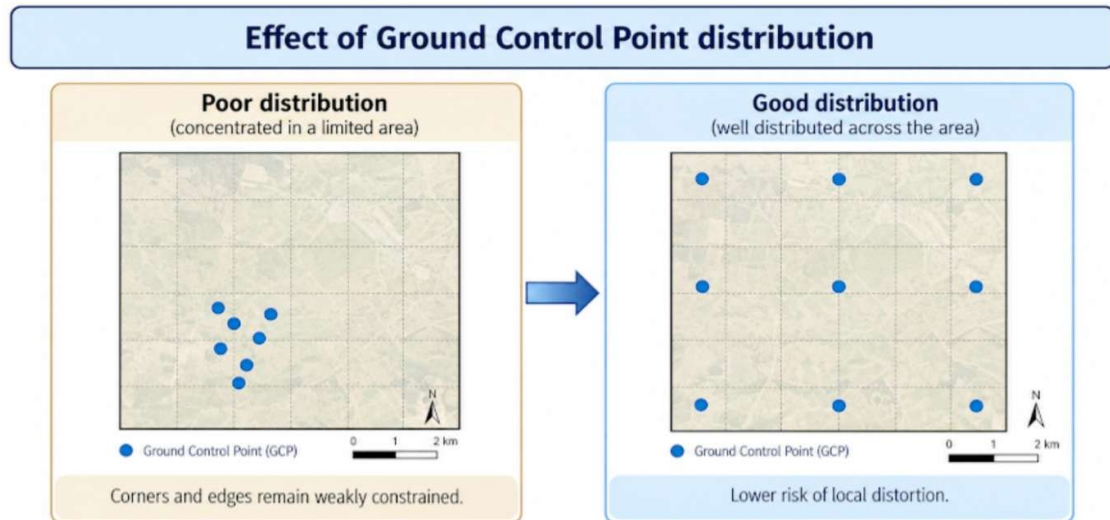


Figure 3.4. Conceptual comparison between poor and good Ground Control Point distribution across a map sheet.

Source: Prepared by the researcher based on Mikhail et al. (2001), Luft and Schiewe (2021), and Bozzano et al. (2024).

3.4 Transformation Models

Transformation models are the mathematical tools used to relate the coordinate space of a source map to that of a target system. In the georeferencing of historical maps, this relationship is necessary because an old sheet generally cannot be placed reliably in a modern GIS environment by visual alignment alone. The map may be affected by differences in coordinate reference, scale, orientation, drafting practice, and physical deformation. A transformation model represents these differences mathematically so that they can be applied to the map coordinates (Mikhail et al., 2001).

The transformation is usually estimated from GCPs because these provide known correspondences between the historical map and the target system. Once a sufficient number of control points has been established, the parameters of a selected model can be computed. The quality of the model should be judged not only by its ability to reduce a numerical error value but also by whether its behavior is consistent with the actual

distortion pattern in the map and with the cadastral purpose of the work (Ghilani and Wolf, 2012).

In general terms, a two-dimensional transformation is represented by Equation (3.2):

$$x = f(x, y), \quad y = g(x, y) \quad (3.2)$$

where (x, y) are the source coordinates, (x', y') are the transformed coordinates, and f and g are the functions that define the selected transformation model. Different models define these functions in different ways, and each model has its own assumptions, strengths, and limitations.

3.4.1 Affine Transformation

The affine transformation is one of the most common linear models used to georeference maps. It accounts for translation, rotation, independent scaling in two directions, and shear. Its two-dimensional form is given in Equations (3.3a) and (3.3b) (Boutoura and Livieratos, 2006; Schowengerdt, 2007):

$$x = a_1 + a_2x + a_3y \quad (3.3a)$$

$$y = b_1 + b_2x + b_3y \quad (3.3b)$$

where a_1 and b_1 are translation terms. The remaining coefficients represent the combined effects of rotation, scale change, and shear. The affine model preserves parallel lines, which makes it useful for many cartographic applications, but it does not preserve distances and angles exactly. In practice, the affine transformation is appropriate when deformation is approximately linear across the map sheet. It can provide a stable and interpretable solution when the historical map has primarily been shifted, rotated, scaled, or sheared. Its relative simplicity also reduces the risk of overfitting and makes the transformation behavior easier to interpret (Ghilani and Wolf, 2012).

The affine model becomes less effective when distortion is local or nonlinear. Many historical cadastral sheets do not deform as a single rigid or linearly stretched surface; instead, they may exhibit local bending or irregular stretching caused by paper deformation or drafting inconsistencies. The affine model may improve the general position of the sheet while still leaving discrepancies in some areas, particularly along edges and between adjacent blocks (Schowengerdt, 2007).

3.4.2 Helmert Transformation

The Helmert transformation is widely used in geodetic work and is commonly referred to as a similarity transformation in two-dimensional applications. It preserves geometric

similarity and contains two translations, one rotation, and one uniform scale factor. Its form is given by Equations (3.4a) and (3.4b) (Boutoura and Livieratos, 2006; Schowengerdt, 2007):

$$x = t_x + s(x\cos\theta - y\sin\theta) \quad (3.4a)$$

$$y = t_y + s(x\sin\theta + y\cos\theta) \quad (3.4b)$$

where t_x and t_y are the translation parameters, s is the scale factor, and θ is the rotation angle. Because the scale factor is uniform, the transformation preserves angles and proportional relationships between features. This makes the model attractive when the goal is to transfer coordinates while preserving the overall shape of the dataset.

The Helmert transformation is particularly useful in datum transformation and geodetic network adjustment, where preservation of the network shape is important. It is also easier to interpret than more flexible models because each parameter has a clear geometric meaning. In cadastral applications, this interpretability is useful because the transformation must be defensible and explainable (Mikhail et al., 2001).

The primary limitation is the assumption of uniform distortion, which is often not satisfied by historical cadastral maps. Greater stretching may occur in one part of a paper sheet than in another, and local irregularities may be introduced by the original survey or drafting process. In such cases, the Helmert transformation may provide a reasonable overall fit but remain inadequate for representing localized deformation (Ghilani and Wolf, 2012).

3.4.3 Polynomial Transformation

A polynomial transformation is applied when the relationship between source and target coordinates is too complex to be adequately represented by a simple linear model. By including higher-order terms, polynomial models can account for nonlinear distortions that may occur in historical maps because of original surveying limitations, drafting effects, scanning, or physical deformation of the paper. Equations (3.5a) and (3.5b) represent a second-order polynomial transformation (Boutoura and Livieratos, 2006; Schowengerdt, 2007):

$$x' = a_0 + a_1x + a_2y + a_3x^2 + a_4xy + a_5y^2 \quad (3.5a)$$

$$y' = b_0 + b_1x + b_2y + b_3x^2 + b_4xy + b_5y^2 \quad (3.5b)$$

For a third-order polynomial transformation, cubic terms are added to the second-order model, providing greater flexibility in representing more complex nonlinear deformation patterns. The third-order transformation can be expressed as:

$$x' = a_0 + a_1x + a_2y + a_3x^2 + a_4xy + a_5y^2 + a_6x^3 + a_7x^2y + a_8xy^2 + a_9y^3 \quad (3.6a)$$

$$y' = b_0 + b_1x + b_2y + b_3x^2 + b_4xy + b_5y^2 + b_6x^3 + b_7x^2y + b_8xy^2 + b_9y^3 \quad (3.6b)$$

where x and y are the source coordinates, x' and y' are the transformed coordinates, a_0 to a_5 and b_0 to b_5 are the coefficients of the second-order transformation, and a_0 to a_9 and b_0 to b_9 are the coefficients of the third-order transformation. The additional cubic terms increase the flexibility of the third-order model and enable it to represent more complex spatial deformation patterns.

The main advantage of a polynomial transformation is its flexibility. It can model stretching, bending, and warping that cannot be adequately represented by affine or Helmert transformations. This is particularly useful for historical maps with nonuniform deformation, especially when physical paper distortion is evident. When a sufficient number of reliable control points are well distributed across the map sheet, a polynomial model may improve the fit in areas where linear models produce relatively large residuals (Schowengerdt, 2007).

However, this flexibility must be used carefully. As the polynomial order increases, the number of transformation parameters also increases, and the solution becomes more sensitive to the quality and spatial distribution of the GCPs. A higher-order model may fit the control points very closely while behaving poorly between them or outside their spatial extent. This condition, commonly referred to as overfitting, is particularly important in cadastral applications, where parcel geometry and boundary continuity must remain spatially coherent rather than merely providing a good statistical fit at selected control points (Ghilani and Wolf, 2012).

The Palestinian case studied by Tamim and Taha (2016) supports this caution. Their results indicated that a second-order polynomial transformation can be useful for scanned Jordanian cadastral block sheets, particularly when an adequate number of suitable control points is available and historical field marks can be identified and measured. This finding should not be interpreted as a general rule that one transformation model is always superior. Instead, model selection should be based on the actual distortion pattern, the number and spatial distribution of control points, and the intended cadastral use of the transformed output (Tamim and Taha, 2016).

3.4.4 Projective Transformation

A projective transformation is used when perspective effects need to be represented. It belongs to the family of rational transformations and is given by Equations (3.7a) and (3.7b) (Boutoura and Livieratos, 2006; Schowengerdt, 2007):

$$x = \frac{a_1x + a_2y + a_3}{c_1x + c_2y + 1} \quad (3.7a)$$

$$y = \frac{b_1x + b_2y + b_3}{c_1x + c_2y + 1} \quad (3.7b)$$

where the coefficients a , b , and c describe the linear and perspective parts of the transformation. The projective model is commonly used in photogrammetry and image rectification because it can compensate for distortions due to camera angle, plane tilt, or perspective viewing geometry (Schowengerdt, 2007).

However, a projective transformation is not always the best choice for cadastral maps. Parcel data require stable boundary relationships, parallelism, and interpretable distances. Because these properties are not preserved in the same way as they are under similarity or affine models, the projective model must be used with caution. It may be useful in some imaging situations but is generally less suitable when preservation of cadastral geometry is the priority (Boutoura and Livieratos, 2006; Schowengerdt, 2007).

3.4.5 Model Selection and Stability

The choice of a transformation model is a methodological decision, not a software decision. It should depend on the type of distortion, the number and quality of control points, the intended use of the output, and the required accuracy. Simple models such as Helmert and affine transformations are generally more stable and easier to interpret, but they cannot represent complex local deformations. More flexible models, such as polynomial transformations, may improve local fit but can become unstable if the control network is weak or unevenly distributed (Ghilani and Wolf, 2012).

In cadastral applications, the best model is not necessarily the one that produces the smallest RMSE. A model may reduce numerical error at the cost of unacceptable changes in the spatial relationships between parcels. Model selection should therefore consider both statistical indicators and cadastral geometry. The transformation should improve positional agreement while preserving, as far as possible, the coherence of parcel boundaries and the fit between neighboring blocks (Brovelli and Minghini, 2012; Janata and Cajthaml, 2021). Good practice therefore involves comparing several models using the same control data, analyzing both the magnitude and spatial distribution of residuals, and then inspecting the transformed map visually and topologically in GIS. This combined evaluation reduces the risk of selecting a model merely because it fits the control points well. Such caution is particularly important for historical cadastral maps, where local distortions can remain hidden when evaluation relies on a single global statistic (Schowengerdt, 2007).

Another lesson from Tamim and Taha (2016) is that a small transformation RMSE should not be confused with complete cadastral accuracy. For example, a transformation may fit the selected control points well while still leaving errors at independent check points or

along parcel boundaries. In this thesis, this distinction is important because the final objective is not only to reduce residuals at GCPs, but also to improve the behavior of adjoining block sheets within one connected cadastral fabric (Tamim and Taha, 2016).

3.5 The Method of Least Squares

The least-squares method is a fundamental tool in geodetic adjustment, surveying, and GIS because it addresses a common practical condition: observations are informative but never error-free. Coordinates obtained from Ground Control Points (GCPs), scanned historical sheets, and field measurements all contain some uncertainty. In georeferencing, this uncertainty cannot be ignored because transformation parameters are typically estimated from more observations than the minimum required by the model. Least squares provides a systematic means of using all available observations while reducing the influence of random error on the final solution (Mikhail et al., 2001; Ghilani and Wolf, 2012).

The idea behind the method is straightforward. The transformation parameters are chosen so that the computed coordinates are, as a whole, as close as possible to the observed reference coordinates. The differences between observed and computed values are called residuals, and the adjustment seeks to minimize the sum of their squares. This can be expressed as:

$$\min \sum_{i=1}^n v_i^2 \quad (3.8)$$

where v_i is the residual of the i -th observation and n is the total number of observations. Squaring the residuals gives greater weight to larger discrepancies and prevents positive and negative errors from canceling one another. The result is not a perfect fit to every point but a balanced solution that best represents the complete observation set (Ghilani and Wolf, 2012; Younis, 2015).

3.5.1 Mathematical Formulation

In georeferencing, the least-squares model can be expressed in a compact matrix form that relates the observations, residuals, and unknown transformation parameters as follows:

$$\ell + \mathbf{v} = \mathbf{A}\hat{\mathbf{x}} \quad (3.9)$$

where ℓ is the vector of observed target-coordinate values, $\mathbf{v}$ is the residual vector, $\mathbf{A}$ is the design matrix formed from the source-map coordinates, and $\hat{\mathbf{x}}$ is the vector of estimated transformation parameters. Each Ground Control Point (GCP) contributes two observation equations, one for the transformed x -coordinate and one for the transformed y -coordinate. The block-matrix forms for the affine, second-order polynomial, and third-order polynomial transformations are given below.

Matrix 3.1. Block-matrix form of the affine transformation observation equations.

$$\begin{bmatrix} x_1 \\ y_1 \\ \vdots \\ x_m \\ y_m \end{bmatrix} + \begin{bmatrix} v_{x_1} \\ v_{y_1} \\ \vdots \\ v_{x_m} \\ v_{y_m} \end{bmatrix} = \begin{bmatrix} 1 & x_1 & y_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & x_1 & y_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_m & y_m & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & x_m & y_m \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ b_1 \\ b_2 \\ b_3 \end{bmatrix}$$

Source: Prepared by the researcher based on Ghilani and Wolf (2012).

For the second-order polynomial transformation, define the polynomial basis row vector for the i th GCP as

$$\mathbf{q}_i^{(2)} = [1 \quad x_i \quad y_i \quad x_i^2 \quad x_i y_i \quad y_i^2].$$

The corresponding observation equations can then be written in the compact block-matrix form shown in Matrix 3.2.

Matrix 3.2. Block-matrix form of the second-order polynomial transformation observation equations.

$$\begin{bmatrix} x_1 \\ y_1 \\ \vdots \\ x_m \\ y_m \end{bmatrix} + \begin{bmatrix} v_{x_1} \\ v_{y_1} \\ \vdots \\ v_{x_m} \\ v_{y_m} \end{bmatrix} = \begin{bmatrix} \mathbf{q}_1^{(2)} & \mathbf{0} \\ \mathbf{0} & \mathbf{q}_1^{(2)} \\ \vdots & \vdots \\ \mathbf{q}_m^{(2)} & \mathbf{0} \\ \mathbf{0} & \mathbf{q}_m^{(2)} \end{bmatrix} \hat{\mathbf{x}}^{(2)}.$$

The second-order parameter vector is

$$\hat{\mathbf{x}}^{(2)} = [a_0 \quad a_1 \quad a_2 \quad a_3 \quad a_4 \quad a_5 \quad b_0 \quad b_1 \quad b_2 \quad b_3 \quad b_4 \quad b_5]^T.$$

Source: Prepared by the researcher based on Boutoura and Livieratos (2006) and Schowengerdt (2007).

For the third-order polynomial transformation, the polynomial basis is extended to include the cubic terms:

$$\mathbf{q}_i^{(3)} = [1 \quad x_i \quad y_i \quad x_i^2 \quad x_i y_i \quad y_i^2 \quad x_i^3 \quad x_i^2 y_i \quad x_i y_i^2 \quad y_i^3].$$

The third-order model is therefore represented by Matrix 3.3.

Matrix 3.3. Block-matrix form of the third-order polynomial transformation observation equations.

$$\begin{bmatrix} x_1 \\ y_1 \\ \vdots \\ x_m \\ y_m \end{bmatrix} + \begin{bmatrix} v_{x_1} \\ v_{y_1} \\ \vdots \\ v_{x_m} \\ v_{y_m} \end{bmatrix} = \begin{bmatrix} \mathbf{q}_1^{(3)} & \mathbf{0} \\ \mathbf{0} & \mathbf{q}_1^{(3)} \\ \vdots & \vdots \\ \mathbf{q}_m^{(3)} & \mathbf{0} \\ \mathbf{0} & \mathbf{q}_m^{(3)} \end{bmatrix} \hat{\mathbf{x}}^{(3)}.$$

The third-order parameter vector is

$$\hat{\mathbf{x}}^{(3)} = [a_0 \quad a_1 \quad a_2 \quad a_3 \quad a_4 \quad a_5 \quad a_6 \quad a_7 \quad a_8 \quad a_9 \quad b_0 \quad b_1 \quad b_2 \quad b_3 \quad b_4 \quad b_5 \quad b_6 \quad b_7 \quad b_8 \quad b_9]^T.$$

Source: Prepared by the researcher based on Boutoura and Livieratos (2006) and Schowengerdt (2007).

In Matrices 3.1-3.3, m denotes the number of GCPs. The design matrix is constructed from the source-map coordinates (x_i, y_i) , while the observation vector contains the corresponding target coordinates (x_1, y_1) . The affine model contains six unknown transformation parameters, the second-order polynomial model contains twelve, and the third-order polynomial model contains twenty. When more GCPs than the mathematical minimum are available, the system becomes overdetermined and all observations can be adjusted simultaneously by least squares. This redundancy improves solution stability and enables the residuals to be examined for weak or inconsistent observations (Ghilani and Wolf, 2012; Schowengerdt, 2007).

3.5.2 Least-Squares Solution and Normal Equations

For the linearized model $\ell + v = A \hat{x}$, the least-squares solution is obtained from the normal equations by minimizing the sum of squared residuals $v^T v$:

$$\hat{x} = (A^T A)^{-1} A^T \ell \quad (3.10)$$

where A^T represents the transpose of the design matrix and $(A^T A)^{-1}$ is the inverse of the normal matrix. The estimated parameters are those that provide the minimum total squared residuals for the observations.

3.5.3 Residuals, Measures of Accuracy and Simultaneous Adjustment

Once the transformation parameters have been estimated, the residuals are computed and examined. This is not merely a formality. Residuals describe the post-adjustment behavior of individual points and often reveal problems that a single RMSE value can conceal. The residual vector is computed as:

$$v = A \hat{x} - \ell \quad (3.11)$$

Small residuals that are distributed without a clear pattern usually indicate that the selected model agrees reasonably well with the control data. A large residual at one point, on the other hand, may indicate incorrect point identification, a field measurement problem, a drafting error in the historical map, or a local distortion that the model cannot represent. For this reason, residual analysis should be interpreted in conjunction with the map itself rather than treated only as a numerical table (Mikhail et al., 2001; Ghilani and Wolf, 2012).

3.6 Accuracy Assessment

Accuracy assessment is the stage at which the georeferencing result is rigorously tested rather than simply accepted. A map may appear well placed on the screen but still have

local displacement, weak areas near its edges, or boundary inconsistencies that are only apparent when the residuals and parcel geometry are examined carefully. In cadastral work, this stage is important because positional error is not merely a cartographic problem. Parcel boundaries, areas, adjacency, and the reliability of land records can all be affected (Ghilani and Wolf, 2012; Sengupta et al., 2016).

Two types of accuracy are particularly relevant here. Absolute accuracy describes how closely transformed coordinates agree with their positions in the adopted reference system. Relative accuracy describes how well neighboring features preserve their correct spatial relationships after transformation. In engineering and cadastral applications, relative accuracy can be as important as absolute accuracy because adjacent parcels must remain mutually consistent even when a small overall shift is present.

3.6.1 RMSE, Residuals, and Bias

One of the most widely used indicators for summarizing positional discrepancy is root-mean-square error (RMSE). For two-dimensional coordinate residuals, it can be expressed as:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n [(x_i - x_i')^2 + (y_i - y_i')^2]} \quad (3.12)$$

where x_i and y_i are reference coordinates, x_i' and y_i' are transformed coordinates, and n is the number of points used in the evaluation.

Although RMSE provides a useful overall measure of positional accuracy and facilitates comparison between transformation models, it should not be interpreted in isolation. A low overall RMSE may still conceal local distortions, particularly near map edges, corners, or areas located between control points. Therefore, the residuals of individual points should also be examined (Schowengerdt, 2007; Ghilani and Wolf, 2012). The residual magnitude for each point can be calculated as:

$$r_i = \sqrt{(\Delta x_i)^2 + (\Delta y_i)^2} \quad (3.13)$$

where $\Delta x_i = x_i - x_i'$ and $\Delta y_i = y_i - y_i'$ are the coordinate differences between the reference and transformed coordinates for point i .

In addition to the residual magnitude of each point, the positional accuracy in the two coordinate directions can be evaluated separately using the root-mean-square error in the x - and y -directions. These measures are calculated as:

$$RMSE_x = \sqrt{\frac{\sum_{i=1}^n (\Delta x_i)^2}{n}} \quad (3.14a)$$

$$RMSE_y = \sqrt{\frac{\sum_{i=1}^n (\Delta y_i)^2}{n}} \quad (3.14b)$$

where n is the total number of points used in the accuracy assessment. The combined two-dimensional planimetric RMSE can then be expressed as:

$$RMSE_{2D} = \sqrt{RMSE_x^2 + RMSE_y^2} \quad (3.15)$$

The values of RMSE_x and RMSE_y describe the error components in the two coordinate directions, while RMSE_{2D} provides a single measure of the overall planimetric positional accuracy. Considering both the component RMSE values and the individual point residuals provides a more reliable assessment of transformation performance than relying on a single overall statistic.

3.6.2 Cadastral Accuracy and Practical Validation

In cadastral applications, statistical measures must be supplemented by geometric and topological inspection. The result should be examined for overlapping parcels, unintended gaps, boundary misalignment, and abnormal changes in parcel shape or area. These checks are not subordinate to numerical evaluation; they are part of the definition of quality in cadastral mapping. A transformation that produces a reasonable RMSE but disrupts the spatial relationship between neighboring parcels is not suitable for this research.

Accordingly, the accuracy assessment in this study combines three forms of evidence: numerical indicators such as RMSE and residuals, statistical indicators such as covariance and error propagation, and GIS-based inspection of topology and boundary continuity. This combined assessment is appropriate for Jordanian cadastral block sheets because their errors are not necessarily uniform. Some parts of a sheet may fit well, while others may require closer review before the data can be used confidently in subsequent adjustment stages.

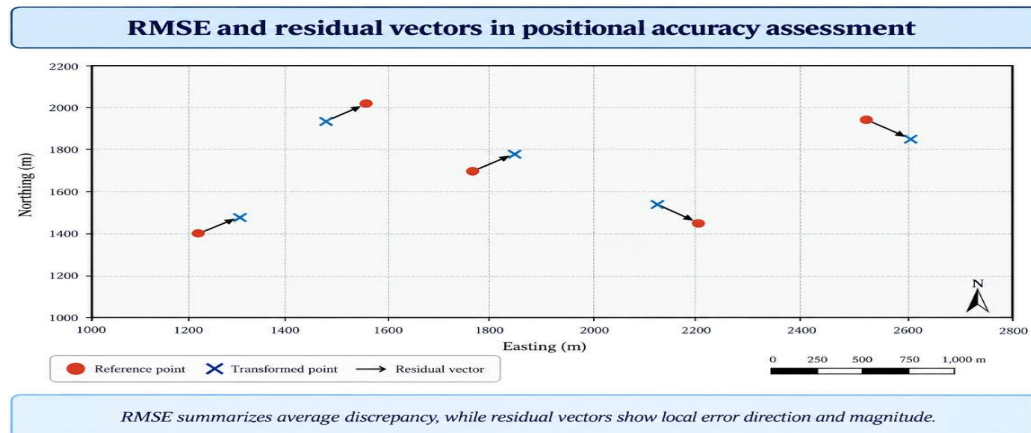


Figure 3.5. Concept of RMSE and residual vectors in positional accuracy assessment.

Source: Prepared by the researcher based on Bozzano et al. (2024) and Brovelli and Minghini (2012).

3.7 Error Sources

All georeferencing processes are subject to error; however, when historical cadastral maps are used, these errors can become particularly significant. The final positional discrepancy is typically not caused by a single source, but rather by the cumulative effects of deficiencies in the original survey, paper-sheet deformation, the quality and distribution of ground control points, datum or reference-system differences, transformation-model assumptions, digitizing operations, and GIS processing. Understanding these sources is essential because the remaining positional error cannot be interpreted correctly without considering its origin (Mikhail et al., 2001; Ghilani and Wolf, 2012).

The principal sources of error that may affect the georeferencing of historical cadastral block sheets are summarized in Figure 3.6.

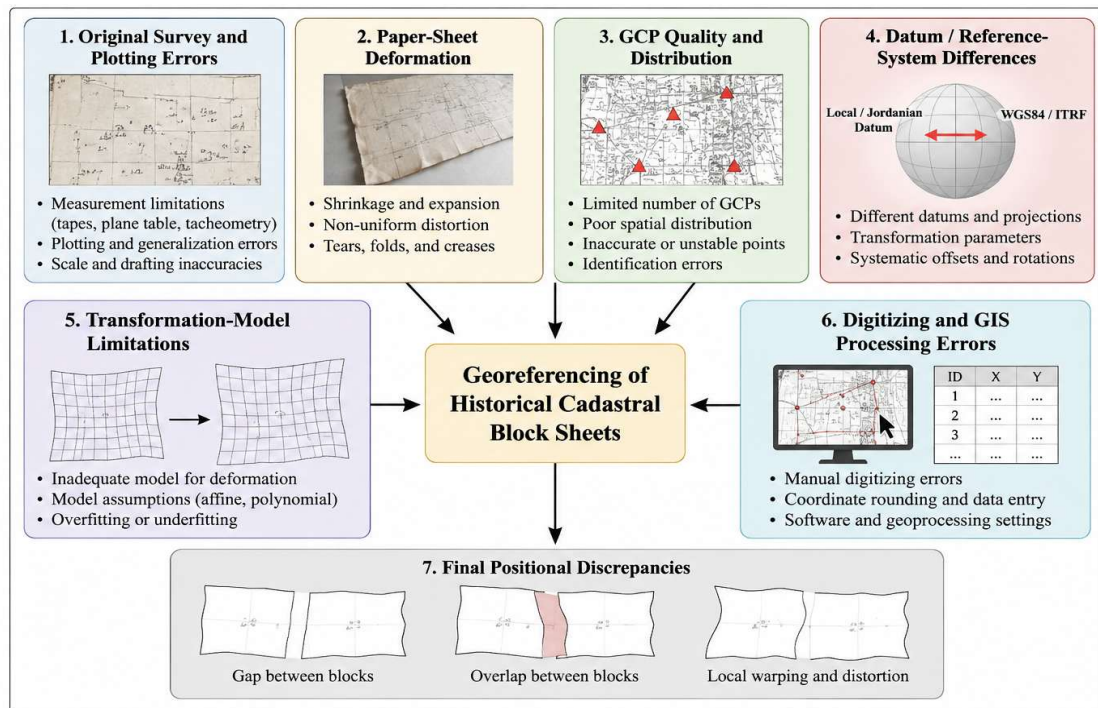


Figure 3.6. Principal sources of error affecting the georeferencing of historical cadastral block sheets.

Source: Prepared by the researcher based on Mikhail et al. (2001), Ghilani and Wolf (2012), and Sengupta et al. (2016).

In the Jordanian cadastral block sheets, these errors may appear as positional shifts, local warping, parcel misalignment, gaps between adjacent blocks, or overlaps along shared cadastral boundaries. These effects are not merely visual; they can influence parcel-area

measurements, boundary re-establishment, and the degree of certainty with which historical cadastral records can be related to modern spatial data (Sengupta et al., 2016).

3.7.1 Error Sources in Historical Jordanian Cadastral Block Sheets

One of the principal sources of positional error is associated with the historical field-surveying methods and the procedures used to prepare the Jordanian cadastral block sheets. During that period, survey work was carried out using equipment and methods such as plane tables, alidades, measuring tapes, and tacheometric surveying. Although these techniques were appropriate for the surveying conditions of the time, their attainable accuracy was lower than that of modern GNSS-based surveying. The accuracy of the final cadastral sheet was also influenced by map scale and by the manual plotting of surveyed points (Jordanian Lands and Survey Department, 1963; Ghilani and Wolf, 2012; Tamim and Taha, 2016). Historical maps generally exhibit greater positional inaccuracy and uncertainty than contemporary geospatial datasets because of limitations associated with their original production and subsequent use (Tucci and Giordano, 2011).

Some cadastral block sheets were prepared at a scale of approximately 1:2500. The effect of a plotting error on the corresponding ground position can be expressed by the map-scale relationship:

$$e_g = M e_p \quad (3.16)$$

where e_p is the plotting error measured on the map, e_g is the equivalent ground error, and M is the denominator of the map scale. For a scale of 1:2500, $M = 2500$. Therefore, a plotting error of 0.2–0.3 mm corresponds to:

$$e_g = 2500 \times (0.2-0.3) \text{ mm} = 500-750 \text{ mm} = 0.50-0.75 \text{ m}$$

This calculation demonstrates that even a small plotting uncertainty on the original cadastral sheet may correspond to a noticeable positional uncertainty on the ground. Empirical studies of analogue-map digitization similarly show that sub-millimetre positional deviations on a map may translate into metre-level differences when expressed in ground units, depending on map scale (Bolstad et al., 1990).

Consequently, part of the discrepancy between historical point positions and modern observations may have existed in the original map before any subsequent deformation, copying, scanning, georeferencing, or digitization occurred. Positional uncertainty in historical spatial data may originate in the source document itself and may subsequently be propagated through later stages of spatial-data processing (Tucci and Giordano, 2011).

However, the plotting-error relationship expressed in Equation (3.16) represents only one component of the positional uncertainty associated with a historical cadastral point. In

practice, the final position of a digitized point may be influenced by errors inherited from the original field survey and map production, manual plotting on the paper sheet, local deformation of the paper medium, scanning and georeferencing, and subsequent point identification and digitization. Positional errors in digital data derived from analogue maps may therefore arise from the source document itself as well as during measurement, registration, transformation, and digitization (Bolstad et al., 1990; Delfgou et al., 2023).

These uncertainty sources can broadly be viewed as production-related uncertainties inherited from the original survey and map preparation, and processing-related uncertainties introduced during scanning, georeferencing, transformation, and digitization. This distinction is consistent with established classifications of uncertainty in historical-map processing (Tucci and Giordano, 2011; Delfgou et al., 2023).

Under the simplifying assumption that the principal uncertainty components are independent or only weakly correlated, their variances may be combined in an approximate positional error-propagation model:

$$\sigma_{point}^2 \approx \sigma_{survey}^2 + M^2(\sigma_{plot,paper}^2 + \sigma_{paper,local}^2) + \frac{M^2(0.0254)^2}{R^2} + \sigma_{dig,screen}^2 \quad (3.17)$$

where σ_{point} is the approximate standard deviation of the final digitized cadastral point expressed in ground units; σ_{survey} represents the uncertainty inherited from the original field survey; $\sigma_{plot,paper}$ is the standard deviation associated with manual plotting on the paper sheet; $\sigma_{paper,local}$ represents local nonuniform deformation of the historical paper; M is the denominator of the map scale; R is the scanning resolution in dots per inch (dpi); and $0.0254/R$ represents the nominal size of one raster pixel on the paper in metres. The term $\sigma_{dig,screen}$ represents the uncertainty associated with identifying and digitizing the point in the digital environment and is assumed here to be expressed directly in ground units. The paper-based terms multiplied by M^2 are converted from paper-space variances to their corresponding ground-space variances through the map scale.

Local deformation of the paper medium may result from dimensional changes associated with temperature, humidity, mounting tension, repeated handling, or other nonuniform physical effects. Manual digitization may also introduce operator-dependent positional variability, while georeferencing can introduce additional displacement when control points or corresponding features cannot be identified perfectly (Bolstad et al., 1990; Delfgou et al., 2023).

Equation (3.17) should therefore be interpreted as an approximate conceptual error budget rather than as a direct estimator of the actual positional error at every cadastral point. Its validity depends on the simplifying assumption that the individual uncertainty components are independent or only weakly correlated and that all terms are expressed in consistent units. In historical cadastral sheets, some error sources may instead contain systematic or spatially correlated components, particularly local paper deformation, reproduction effects, control-point uncertainty, and reference-system discrepancies. Historical-map studies also show that positional uncertainty is not necessarily spatially uniform across an entire map (Tucci and Giordano, 2011).

Accordingly, Equation (3.17) is used primarily to explain how several sources of uncertainty may contribute to the final positional uncertainty rather than to predict the exact error of an individual cadastral point. The actual accuracy achieved in this study is evaluated empirically using residual analysis, RMSE, independent Ground Check Points, and withheld Check Tie Points.

For example, if a historical cadastral sheet is scanned at a resolution of $R = 300$ dpi, the nominal size of one raster pixel on the paper is $0.0254/300 = 0.0000847$ m = 0.0847 mm. At a map scale of 1:2500, this nominal pixel dimension corresponds to an approximate ground dimension of $2500 \times 0.0000847 \approx 0.212$ m, or approximately 21.2 cm per pixel on the ground.

This value does not represent the total positional error of the cadastral point. Rather, it illustrates the scale-dependent magnitude associated with raster resolution within the broader positional uncertainty budget. The actual point error may be larger or smaller depending on the combined effects of the original survey, graphical plotting, paper deformation, scanning, georeferencing, point identification, digitization, control quality, and subsequent transformation. Digital-map-processing studies likewise emphasize that uncertainty may arise at several stages, beginning with the original map production and continuing through scanning, georeferencing, and feature extraction or digitization (Delfgou et al., 2023).

An example of a positional discrepancy between historical cadastral information and corresponding modern reference data in the study area is illustrated in Figure 3.7 using GIS data from one of the investigated cadastral blocks.

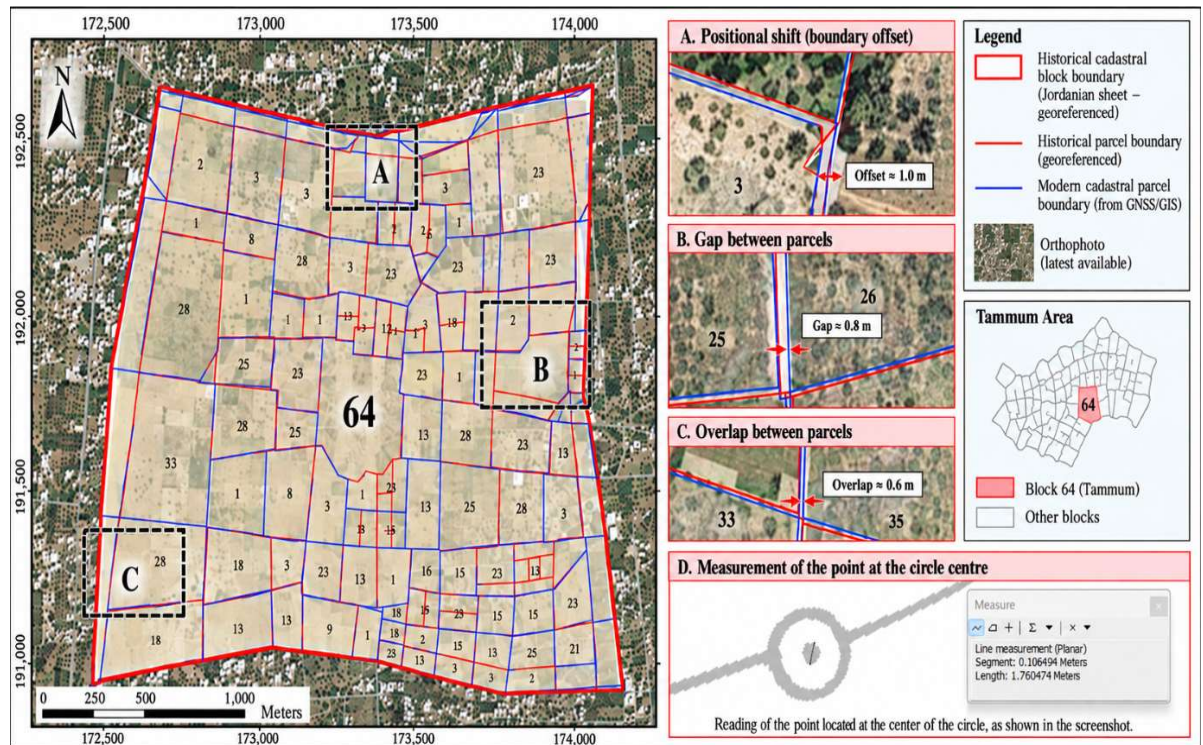


Figure 3.7. Positional discrepancies between historical (Jordanian) and modern cadastral parcels in Block 64, Tammun, with examples of boundary offset (A), gap (B), overlap (C), and measurement of the point at the circle center (D). Source: Prepared by the researcher from the GIS data used in this study.

3.7.2 Errors Related to Control Points and Reference Systems

Ground Control Points are among the most sensitive elements in the entire workflow. Any error in point identification, coordinate measurement, or correspondence between the historical sheet and the modern dataset is propagated directly into the transformation parameters. Spatial distribution is equally important. When control points are concentrated in one area of a sheet, the transformation may perform well locally but poorly near the edges or in areas with fewer constraints (Bozzano et al., 2024).

Reference-system errors can have similar effects. When datasets based on older local datums are compared with modern GNSS-based coordinates, an appropriate datum transformation is required. Misidentifying the datum or projection can produce a shift that is incorrectly interpreted as map distortion. Therefore, the quality of any transformation result should be verified by checking the coordinate system, datum, and projection (Ghilani and Wolf, 2012; Younis, 2020).

3.7.3 Model, Digitizing, and Processing Errors

Ground Control Points (GCPs) are among the most significant elements of the georeferencing process. Any error in identifying a location on the historical map, measuring its coordinates in the field, or matching the same location in the modern dataset

can affect the transformation parameters and the final map position. Their spatial distribution is also crucial. If most control points are clustered in one area, the transformation may perform well near that cluster but poorly near sheet edges and corners. Therefore, selected control points should be clear, stable, accurately measured, and well distributed across the cadastral sheet (Ghilani and Wolf, 2012; Bozzano et al., 2024).

Another source of inaccuracy is the physical condition of the historical paper sheet. Repeated use and long-term storage can expose cadastral maps to humidity, temperature variation, folding, physical damage, expansion, and shrinkage. Repeated copying and scanning may also alter the map's original size and shape. These changes are generally nonuniform, with some areas affected more strongly than others. Consequently, a transformation may improve the overall position of a block while local discrepancies persist within the sheet or along its boundaries (Mikhail et al., 2001; Schowengerdt, 2007; Tamim and Taha, 2016).

Cadastral-map accuracy is also influenced by map scale and the manual plotting of surveyed positions. Many Jordanian cadastral block sheets were produced at a scale of approximately 1:2500. At this scale, a plotting uncertainty of 0.2–0.3 mm on the map is equivalent to approximately 0.50–0.75 m on the ground. This indicates that part of the positional discrepancy may have existed when the points and boundaries were originally plotted. Subsequent paper deformation, copying, and scanning may have introduced further changes to the original map (Jordanian Lands and Survey Department, 1963; Ghilani and Wolf, 2012; Tamim and Taha, 2016).

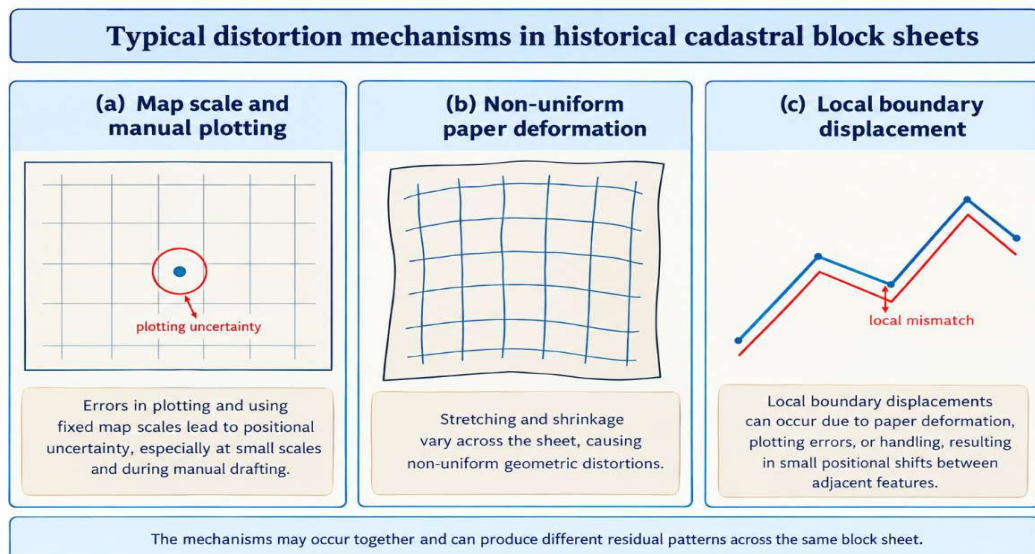


Figure 3.8. Schematic illustration of map-scale, manual-plotting, and local paper-deformation effects in historical cadastral block sheets.

Source: Prepared by the researcher as a schematic synthesis of the error mechanisms discussed in this section.

Errors may also arise from the reference system and the historical geodetic network on which the cadastral maps were based. Historical cadastral surveys in Palestine used the Palestine 1923 Grid, which was established through classical triangulation and traverse observations. Consequently, the coordinate accuracy of historical block sheets depends not only on field-survey precision and plotting procedures but also on the accuracy and stability of the original geodetic control points.

The historical Palestinian geodetic network was established between the 1920s and 1947, and its points were affected over time by crustal movement and other local changes (Younis, 2020). Relative displacement between some network locations can reach approximately 30 cm. This value should not be interpreted as a drawing error in every block; rather, it demonstrates that the original geodetic network itself may differ from modern GNSS coordinates. The same analysis showed that one of the best transformations from modern GNSS coordinates to the Palestine 1923 Grid achieved accuracies of approximately 20 cm in easting, 30 cm in northing, and 37 cm in horizontal position.

A mismatch between a historical cadastral map and contemporary field measurements should therefore not automatically be attributed to deformation of the paper sheet. It may arise from several sources, including the original survey, manual plotting, map scale, paper deformation, incorrect identification of control points, limitations of the historical geodetic network, or errors in transformations between reference systems. Accordingly, the coordinate system, datum, projection, control points, and physical condition of the historical map should all be verified when evaluating the final georeferencing result (Ghilani and Wolf, 2012; Younis, 2020).

3.7.4 Interaction and Mitigation of Errors in Cadastral Work

In practice, the sources of error in georeferencing do not act independently. Poor model selection combined with a weak control-point network may produce greater error than either factor alone. Likewise, a datum mismatch may be hidden within residual patterns and incorrectly interpreted as paper deformation. Therefore, the georeferencing of historical cadastral sheets requires not only numerical correction but also professional interpretation of the spatial data and the condition of the historical map (Mikhail et al., 2001).

Several measures can be taken to reduce the effects of these errors. The most important include the selection of stable and well-distributed control points; verification of the

coordinate reference system before transformation; use of an appropriate transformation model; application of least-squares adjustment; inspection of residuals; and examination of the final parcel configuration in GIS for overlaps, gaps, and boundary misalignment. These steps form essential quality-control procedures in the present research because the objective is to achieve reliable boundary reconstruction and to support the subsequent simultaneous adjustment of the georeferenced Jordanian cadastral blocks.

3.8 Integration with Geographic Information Systems (GIS)

Once historical cadastral maps are georeferenced, they can be treated as spatial data within a GIS environment. At this stage, the output is no longer merely a corrected image or a list of transformed coordinates but a spatial layer that can be compared with current survey data, orthophotos, administrative layers, and other geographic datasets. An example of this integration is illustrated in Figure 3.9.

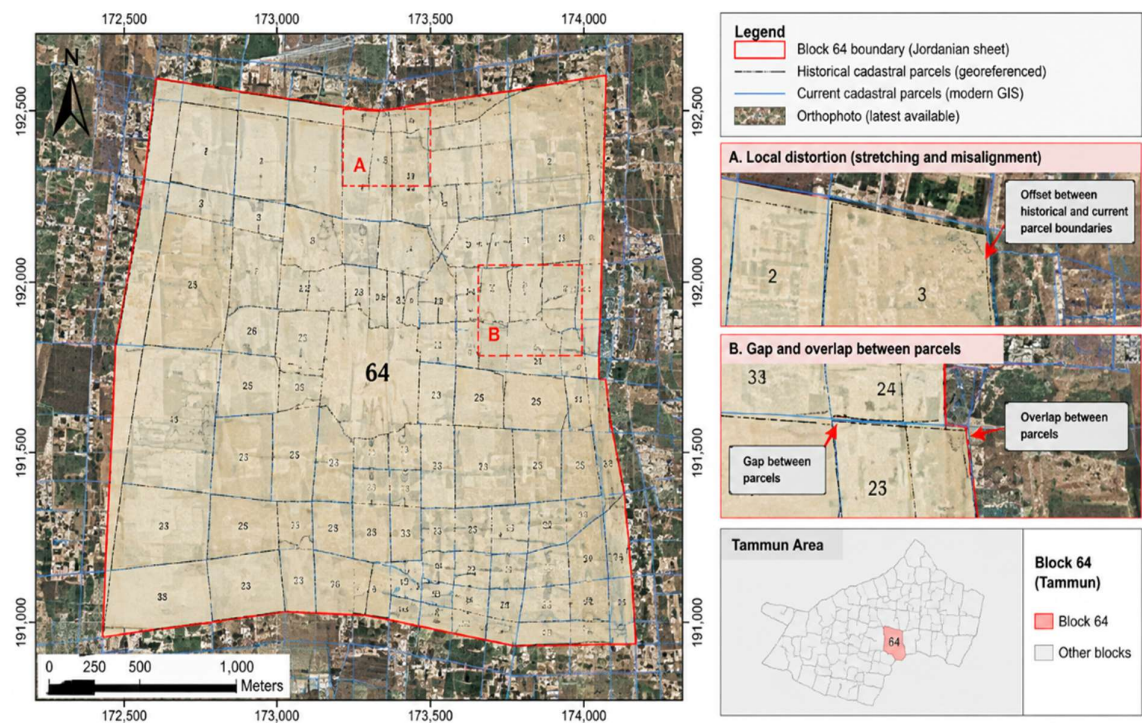


Figure 3.9. Example of integrating a georeferenced historical cadastral block sheet with modern GIS layers (Tammun Block 64).

Source: Prepared by the researcher from the Jordanian cadastral sheet of Tammun Block 64, modern cadastral data, and an orthophoto in GIS.

Source: Prepared by the researcher from the GIS data used in this study.

The integration of historical cadastral data into GIS is important because the purpose of the research is not only to transform old sheets into a modern coordinate system but also to

assess how well they can be incorporated into the present cadastral framework. GIS enables the transformed cadastral boundaries to be overlaid with modern spatial datasets, allowing the researcher to inspect positional agreement, identify local gaps or overlaps, and evaluate the continuity of shared boundaries between adjacent blocks (Longley et al., 2015; Sengupta et al., 2016).

In the present study, GIS therefore serves both as a georeferencing environment and as a validation platform. It supports the visual and numerical examination of transformed control points, parcel boundaries, residual patterns, and the spatial relationship between neighboring cadastral blocks. This stage is particularly important before the blocks enter the boundary-conditioned least-squares procedure used in the subsequent analysis.

3.8.1 Spatial Data Integration and Management

GIS provides an operational framework for combining datasets of different ages, formats, scales, and accuracies. In this study, these datasets may include scanned Jordanian cadastral block sheets, digitized parcel boundaries, GNSS-derived control points, field observations, aerial photographs, and modern cadastral layers. By integrating these sources within a common reference framework, GIS enables controlled comparison of historical and contemporary spatial information rather than requiring each source to be handled separately.

Data can also be stored and managed effectively within the same environment. Cadastral information is usually represented by vector features, particularly parcel polygons, boundary lines, and control points. These geometries can be linked to descriptive attributes such as block number, parcel number, land use, and administrative notes. This connection between geometry and attributes is one reason GIS is valuable for land administration: a parcel is both a spatial object and an information record (Longley et al., 2015).

3.8.2 GIS-Based Evaluation and Integration of Adjusted Cadastral Blocks

In this research, GIS provides the working environment in which the adjusted Jordanian cadastral blocks are examined as a connected spatial system. It supports evaluation of georeferencing results, detection of remaining overlaps and gaps, comparison of historical and modern parcel patterns, and preparation of data for the simultaneous adjustment stage. This is important because the study addresses not only the accuracy of individual sheets but also the consistency between neighboring blocks.

In this way, the GIS stage connects the mathematical component of the study with its cadastral significance. Least squares may provide the best estimate of the transformation parameters, but GIS is needed to determine whether the resulting geometry is suitable for

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cadastral interpretation. Combining numerical accuracy, residual analysis, and GIS-based topology checks makes the final evaluation more realistic and better aligned with the practical needs of land administration in Palestine (Longley et al., 2015; Janata and Cajthaml, 2021).

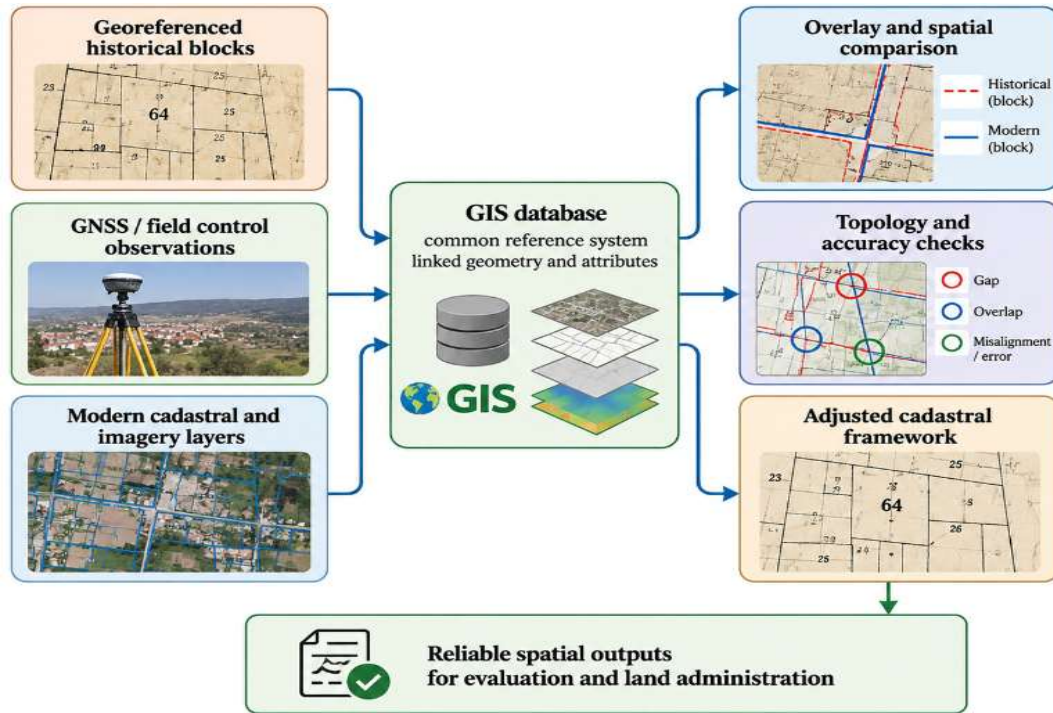


Figure 3.10. GIS-based integration workflow of georeferenced and adjusted cadastral blocks.
Source: Prepared by the researcher.

4.1 Introduction

Chapter 3 presented the theoretical basis of georeferencing, coordinate transformation, and accuracy assessment. This chapter describes the methodology developed to enhance the spatial consistency of historical Jordanian cadastral block sheets. Preliminary georeferencing positions each sheet within the adopted coordinate reference system; however, independent sheet-by-sheet transformation can produce gaps, overlaps, and positional discrepancies along shared block boundaries. The proposed methodology therefore treats adjacent sheets as components of a single connected cadastral fabric.

The adjustment model is formulated as a least-squares problem with boundary constraints. Field-surveyed Control Points anchor each block to the adopted coordinate reference system, while Control Tie Points on common cadastral vertices connect adjacent sheets. In the implemented Affine, Poly2, and Poly3 solutions, the unknowns are the transformation coefficients of all connected blocks; each Control Tie contributes equality conditions requiring the two transformed representations of the same shared vertex to coincide.

The chapter describes the methodological framework, assumptions, mathematical formulation, boundary-condition equations, the general linearization framework, and the connected least-squares solution used for the reported models, together with the procedures used for accuracy and topological quality control. The application of this framework to the selected Tammun blocks is presented in Chapter 5.

4.2 Methodological Framework

A cadastral block sheet is not intended to function as a stand-alone drawing; it is linked to adjoining sheets through parcel relationships and shared boundaries. If adjoining sheets disagree along common edges, improving the fit to control points on each sheet independently will not resolve the inter-block discrepancy. The framework presented here begins with approximate coordinates generated by preliminary georeferencing, proceeds to the identification of reliable control and tie points, and then performs a single simultaneous adjustment of all adjoining sheets.

For the reported MapGeoref implementation, the unknown vector consists of the transformation coefficients of all connected blocks. Each enabled Ground Control Point contributes easting and northing observation equations to its block transformation, while each Control Tie contributes two inter-block equality equations requiring the transformed

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coordinates of the same shared point to agree. Ground Check Points and Check Tie Points remain outside parameter estimation and are used only for validation. Final evaluation combines residual diagnostics, independent Check Point accuracy, and shared-boundary continuity; polygon topology and parcel-area checks are applied only where the required polygon data are available.

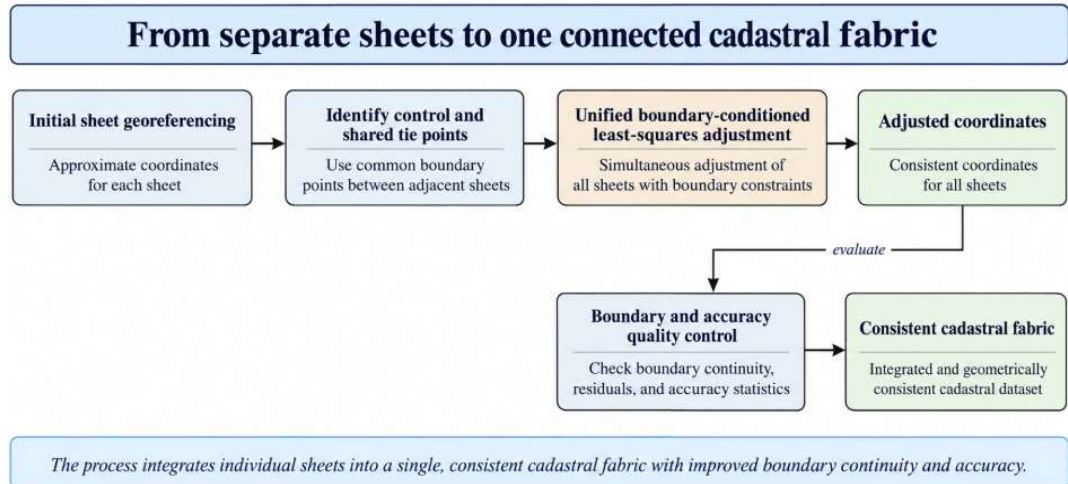


Figure 4.1. General workflow of the proposed methodology.

Source: Prepared by the researcher.

Table 4.1. Main inputs and methodological roles in the proposed framework.

Input or Component	Typical Source	Role in the Proposed Method
Approximate coordinates	Initial georeferencing	Provide starting values for the iterative adjustment.
Control points	Independent field observations	Anchor the network to the adopted modern coordinate system.
Control tie points	Identifiable shared cadastral vertices selected for the simultaneous adjustment	Connect adjacent sheets and enforce coordinate coincidence at shared points.
Check tie points (CTPs)	Shared cadastral vertices intentionally withheld from the boundary constraints	Provide independent inter-block validation by comparing coordinates computed from the neighboring block transformations before and after simultaneous adjustment.
Shared boundary topology	Adjacent block sheets	Support boundary continuity and the detection of gaps and overlaps.
Independent check points	Field observations excluded from the adjustment	Provide an external assessment of positional accuracy.

Source: Prepared by the researcher.

4.2.1 Methodological Assumptions

The procedure relies on the following assumptions: starting coordinates obtained from preliminary georeferencing are sufficiently accurate for the selected formulation; shared cadastral vertices can be identified correctly on neighboring sheets; control and check

points are independent and properly grouped; tie points are distributed along common boundaries rather than clustered in a localized area; and the selected sheets form a continuous adjustment network. Local distortion may exist within historical sheets; therefore, the adjusted solution is evaluated both numerically and topologically. Candidate shared points are also partitioned before adjustment into Control Tie Points and Check Tie Points. The latter must remain excluded from the boundary-condition system so that subsequent inter-block validation is independent of the adjustment.

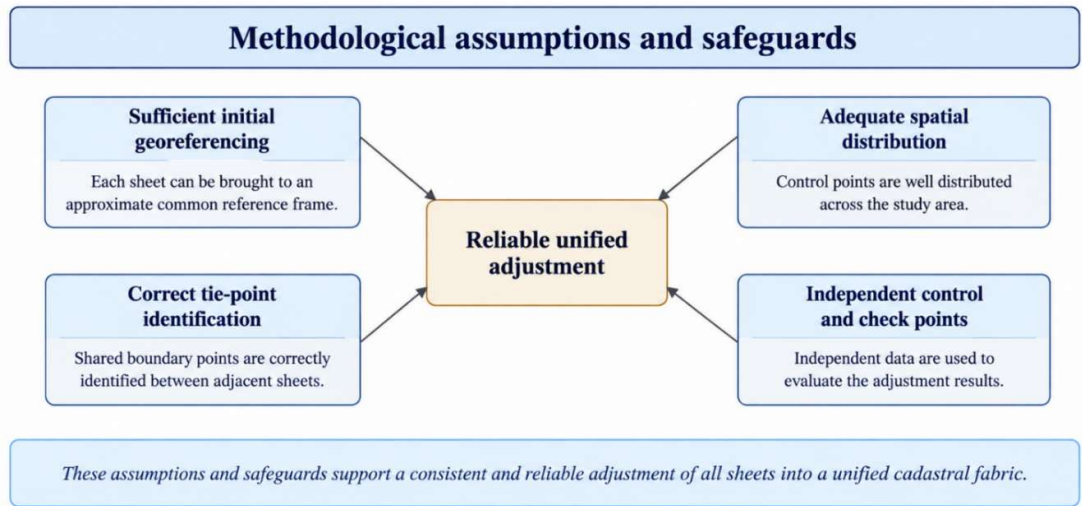


Figure 4.2. Main assumptions supporting the proposed methodology.
Source: Prepared by the researcher.

4.3 Mathematical Formulation of the Adjustment Model

The adjusted coordinate vector is defined in Equation (4.1). Each point contributes an easting and a northing component to the unified solution.

$$X = [x_1 \ y_1 \ x_2 \ y_2 \ \dots \ x_n \ y_n]^T \quad (4.1)$$

where x_i and y_i are the adjusted coordinates of point i and n is the number of points included in the connected adjustment. Let $r(X)$ denote the coordinate-residual vector formed from the differences between the adjusted coordinates and the available coordinate evidence. The least-squares objective is given in Equation (4.2).

$$\min \Phi(X) = r(X)^T r(X) \quad (4.2)$$

The minimization is subject to the boundary-coincidence conditions in Equation (4.3).

$$c(X) = 0 \quad (4.3)$$

In Equation (4.3), $c(X)$ is the vector of condition functions associated with shared tie points. Thus, the functional model combines a least-squares fit to the coordinate evidence with explicit equality conditions that preserve coincidence at common cadastral vertices. Every equation and matrix used below is introduced and interpreted at its point of use.

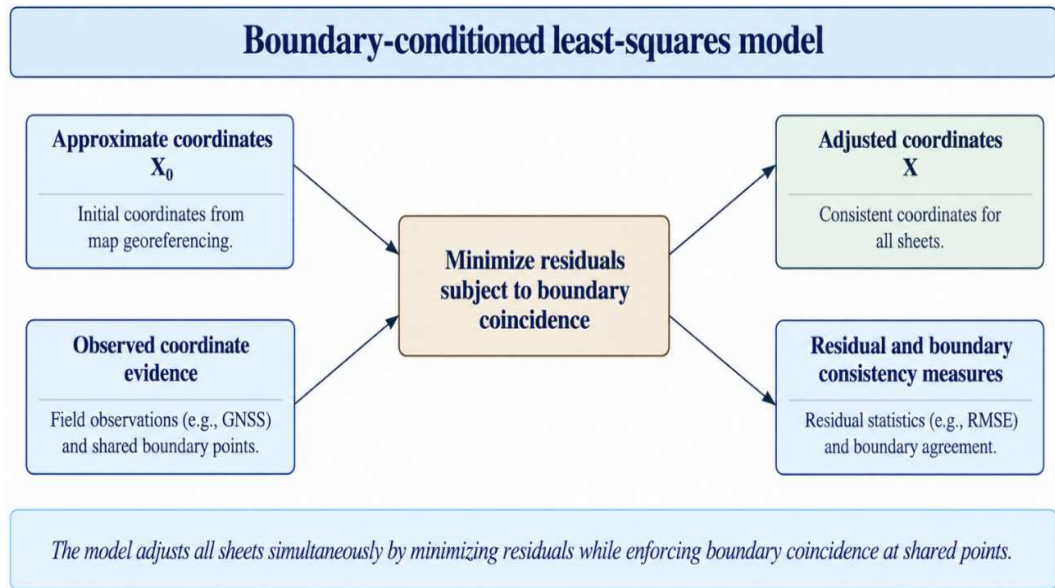


Figure 4.3. Main components of the boundary-conditioned adjustment model.

Source: Prepared by the researcher.

4.4 Boundary-Condition Equations for Unified Adjustment

The boundary conditions represent cadastral relationships that must hold after adjustment. In the adopted model, these relationships are defined by requiring correctly identified tie points on common block boundaries to coincide.

4.4.1 Tie Points and Inter-Block Continuity

A tie point is a cadastral vertex identifiable on two neighboring historical sheets. It differs from a ground control point because its present-day ground coordinates do not need to be independently known. What must be established is that the point depicted on both sheets represents the same physical or legally defined cadastral location. Tie points are selected at unambiguous parcel corners, boundary intersections, cadastral marks, or other repeatable features and are distributed along the common edge.

For adjustment and validation, the shared points are assigned one of two roles. A Control Tie Point is included in the simultaneous boundary-condition equations and contributes directly to the estimation of the connected block transformations. A Check Tie Point (CTP) represents the same type of shared cadastral feature but is intentionally excluded from those equations. Its purpose is to test whether the adjustment improves the relative position of neighboring blocks at locations that did not constrain the solution.

This distinction prevents an in-solution tie residual from being interpreted as independent validation. Residuals of Control Tie Points describe how well the estimated transformation

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satisfies the constraints used in the adjustment; CTP discrepancies provide an external inter-block test because the CTPs do not participate in parameter estimation.

For tie point p represented on sheets A and B, coincidence of the adjusted easting and northing is imposed by Equations (4.4a) and (4.4b).

$$c_{x,p}(X) = x_{p,A} - x_{p,B} = 0 \quad (4.4a)$$

$$c_{y,p}(X) = y_{p,A} - y_{p,B} = 0 \quad (4.4b)$$

The initial discrepancy is expressed compactly by the tie-point discrepancy vector in Equation (4.5), rather than by separate unreferenced component equations.

$$\Delta X_{T,p}^0 = X_{p,A}^0 - X_{p,B}^0 = [x_{p,A}^0 - x_{p,B}^0 \quad y_{p,A}^0 - y_{p,B}^0]^T \quad (4.5)$$

The magnitude of the initial planar separation is the Euclidean norm of this vector, as shown in Equation (4.6).

$$d_p^0 = \|\Delta X_{T,p}^0\| \quad (4.6)$$

For m tie points along an interface, the overall pre-adjustment mismatch is summarized by Equation (4.7).

$$RMSE_Tie^0 = \sqrt{[(1/m) \sum_{p=1}^m \|\Delta X_{T,p}^0\|^2]} \quad (4.7)$$

These quantities diagnose the initial condition of the sheet interface and help identify questionable matches. They are not independent control coordinates. A convenient starting coordinate for a tie point is the arithmetic mean of its two preliminary representations, as stated in Equation (4.8).

$$X_p^0 = \frac{1}{2}(X_{p,A}^0 + X_{p,B}^0) \quad (4.8)$$

The mean in Equation (4.8) is only an initial value. The final coordinate is obtained from the simultaneous solution for the entire connected network. Consequently, a correction at one shared point can influence the geometry of both neighboring sheets while the boundary-coincidence conditions remain satisfied.

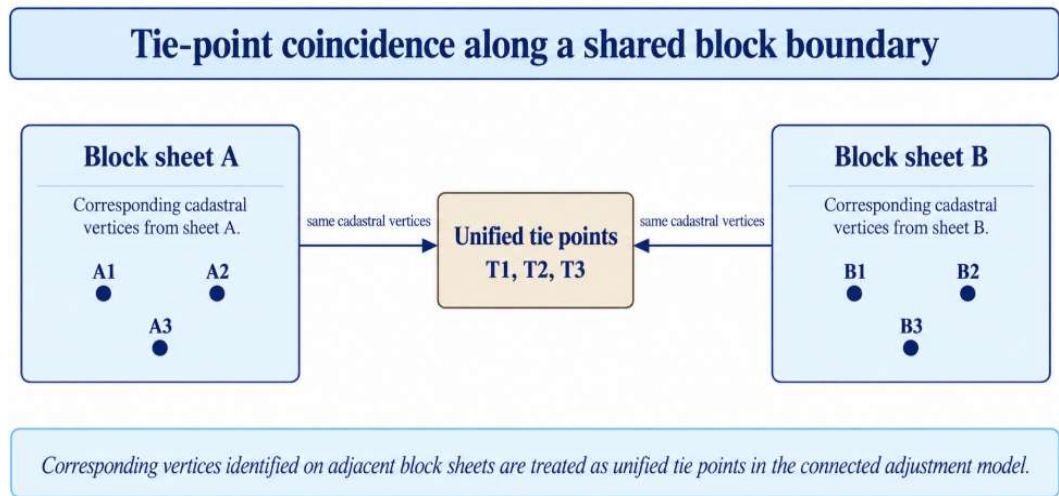


Figure 4.4. Unified treatment of adjacent sheets through shared tie points.

Source: Prepared by the researcher.

Table 4.2. Boundary conditions and their cadastral roles in the proposed model.

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Condition type	General expression	Meaning	Cadastral purpose
Tie-point coincidence	$x_{p,A} - x_{p,B} = 0$ $y_{p,A} - y_{p,B} = 0$	Two representations of the same tie point are forced to converge to one adjusted position.	Eliminates positional discrepancies at shared vertices.
Boundary coincidence	Implemented through tie-point coincidence at shared boundary vertices.	Adjacent sheets share one geometrically consistent adjusted boundary.	Reduces gaps and overlaps and preserves topological continuity between neighboring blocks.

Source: Prepared by the researcher.

4.5 Linearization and Adjustment Solution Strategy

Equations (4.9)–(4.12) present a general iterative extension of the boundary-conditioned framework for cases in which the transformation or condition functions are nonlinear in the unknowns. This form is retained for theoretical completeness but was not used for the reported Affine, Poly2, and Poly3 experiments.

$$X_{k+1} = X_k + \Delta X_k \quad (4.9)$$

For such a nonlinear extension, the residual and boundary-condition functions are linearized around the current approximation using Equation (4.10), with J_k and C_k representing the corresponding Jacobian matrices.

$$r(X_k + \Delta X_k) \approx r_k + J_k \Delta X_k, \quad c(X_k + \Delta X_k) \approx c_k + C_k \Delta X_k \quad (4.10)$$

The constrained normal system in Equation (4.11) then provides the corrections and Lagrange multipliers for that general nonlinear case.

$$\begin{bmatrix} J_k^T J_k & C_k^T \\ C_k & 0 \end{bmatrix} \begin{bmatrix} \Delta X_k \\ \lambda \end{bmatrix} = \begin{bmatrix} -J_k^T r_k \\ -c_k \end{bmatrix} \quad (4.11)$$

If this nonlinear extension were used, the solution would be updated using Equation (4.9), and the procedure would be repeated until the convergence criteria in Equation (4.12) were satisfied.

$$\max_i |\Delta X_{k,i}| < \varepsilon_X \quad \text{and} \quad \max_j |c_j(X_{k+1})| < \varepsilon_c \quad (4.12)$$

In the implemented MapGeoref experiments, however, the Affine, Poly2, and Poly3 transformation coefficients enter the observation and Control Tie equations linearly and are solved directly in one connected least-squares system; numerical iteration tolerances are therefore not part of the reported final runs.

4.5.1 Computational Procedure

The implemented computational procedure includes importing source and field coordinates; classifying Ground Control Points, Ground Check Points, Control Tie Points, and Check Tie Points; assembling a single connected transformation-coefficient system for all blocks; adding easting and northing observation rows for each enabled Ground Control Point; adding two zero-difference equations for each Control Tie group; solving the

assembled least-squares system directly; computing Control Point and Control Tie residuals; and evaluating the excluded Ground Check Points and Check Tie Points. This procedure was used for the Affine, Poly2, and Poly3 results reported in Chapter 5.

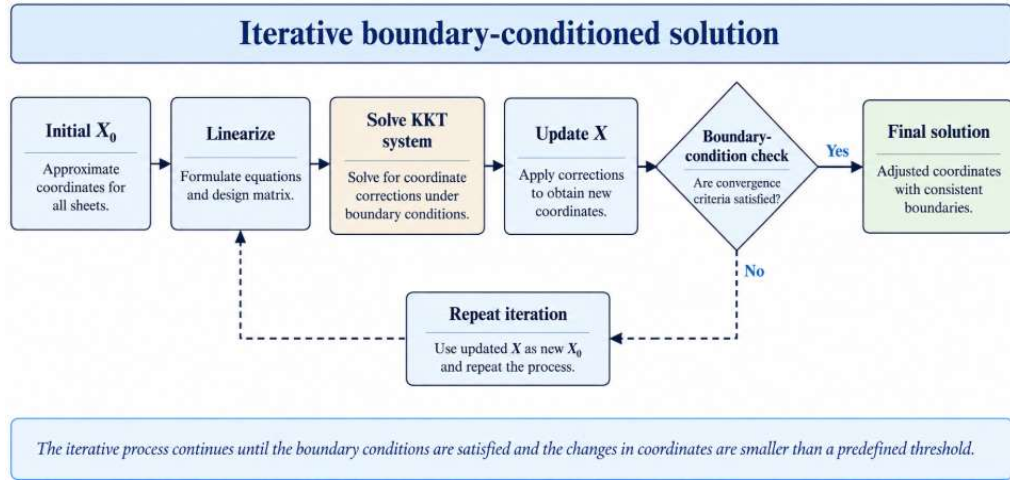


Figure 4.5. General iterative extension of the boundary-conditioned least-squares framework.

Source: Prepared by the researcher.

4.6. Positional Accuracy Assessment

External positional accuracy is assessed using n independent Ground Check Points that were not included in the adjustment. The directional and planar root-mean-square errors are calculated using Equations (4.13a)–(4.13c).

$$RMSE_x = \sqrt{[(1/n) \sum_{i=1}^n (x_i - x_{i,ref})^2]} \quad (4.13a)$$

$$RMSE_y = \sqrt{[(1/n) \sum_{i=1}^n (y_i - y_{i,ref})^2]} \quad (4.13b)$$

$$RMSE_{2D} = \sqrt{RMSE_x^2 + RMSE_y^2} \quad (4.13c)$$

$RMSE_{2D}$ provides a single measure of planar positional accuracy, while $RMSE_x$ and $RMSE_y$ reveal directional behavior. Chapter 5 compares these measures before and after the unified adjustment.

Relative inter-block accuracy is assessed independently with Check Tie Points. For a CTP represented on adjacent blocks A and B, the two transformations are applied separately to its source-image coordinates to obtain (X_A, Y_A) and (X_B, Y_B) . The CTP discrepancy components are $\Delta X_{CTP} = X_A - X_B$ and $\Delta Y_{CTP} = Y_A - Y_B$, and the planar discrepancy is $d_{CTP} = \sqrt{(\Delta X_{CTP})^2 + (\Delta Y_{CTP})^2}$. These quantities are computed once from the independent block solutions and again after the simultaneous adjustment while the CTP remains excluded from the boundary conditions.

For n CTP pairs, $RMSE_{CTP,X}$ and $RMSE_{CTP,Y}$ are obtained from the corresponding component differences, and $RMSE_{CTP,2D} = \sqrt{RMSE_{CTP,X}^2 + RMSE_{CTP,Y}^2}$. The relative improvement is reported as $100 \times (RMSE_{CTP,2D, independent} - RMSE_{CTP,2D, simultaneous}) / RMSE_{CTP,2D, independent}$. A positive value indicates

that the connected adjustment improved agreement at shared locations that were not used as constraints.

4.7 Methodological Strengths and Limitations

The principal advantage of the methodology is that it represents contiguous cadastral sheets as a single connected fabric. Shared vertices are solved simultaneously, and boundary continuity is enforced directly rather than merely checked after independent transformations. The method is transparent because each tie point, residual, coordinate correction, and boundary-condition value can be inspected and reported. The combination of Control Tie Points and withheld CTPs also makes it possible to distinguish internal constraint satisfaction from independent inter-block prediction.

The method depends on correct tie-point identification, adequate distribution of common points, suitable approximate coordinates, and sufficient control to anchor the network. Sparse or erroneous tie-point matches can propagate error across connected sheets. The simultaneous solution is also more computationally demanding than conventional sheet-by-sheet georeferencing and requires systematic quality control. These limitations are addressed through independent Check Points, residual review, topology tests, and sensitivity checks during implementation. The CTP subset must be well distributed along the interfaces and must never be reintroduced as an active tie in the solution used to evaluate it.

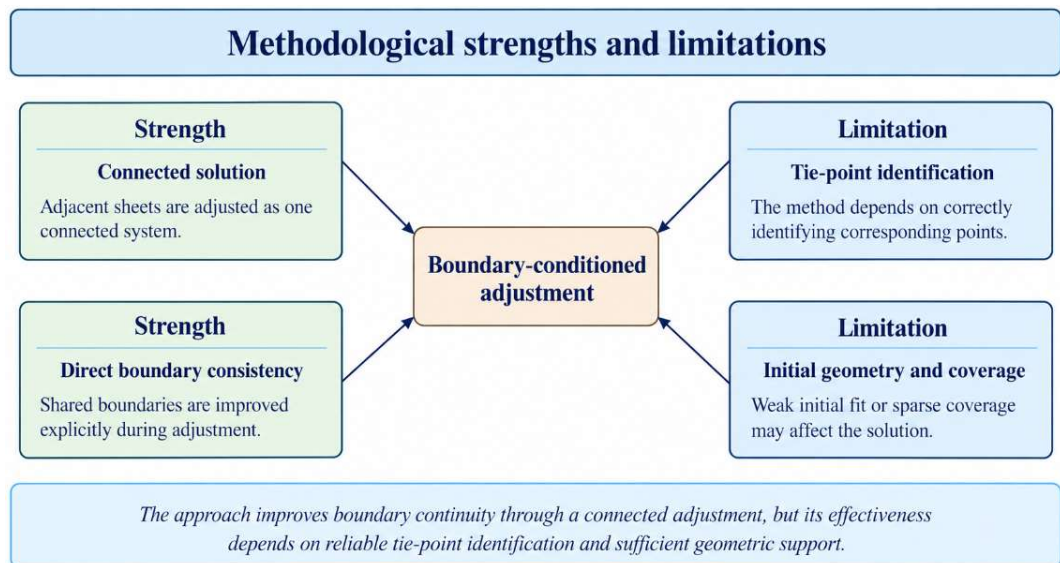


Figure 4.6. Principal strengths and limitations of the proposed methodology.

Source: Prepared by the researcher.

4.8 Summary

Methodology

This chapter established the boundary-conditioned least-squares framework for connecting historical Jordanian cadastral block sheets. The general coordinate formulation explains the adjustment principle, while the reported Affine, Poly2, and Poly3 results were obtained from one connected linear least-squares system whose unknowns are the transformation coefficients of the six blocks. Ground Control Points and Control Tie Points contribute to estimation, whereas Ground Check Points and Check Tie Points remain excluded from estimation and are reserved for validation. Chapter 5 presents the application and results.

Chapter 5

Results and Discussion

5.1 Introduction

This chapter presents the results obtained by applying the developed method to georeference historical Jordanian cadastral block sheets within a single connected solution. The surveying and cadastral implications of these results are then discussed. Because interpretation of the results depends on understanding how they were produced, the implementation workflow is first documented in a concise and systematic manner. The workflow begins with identifying physical features recognizable both on the ground and on the paper sheets, continues through preliminary GIS-based georeferencing, and concludes with simultaneous boundary-conditioned adjustment in the developed application. Quantitative and spatial results are then compared with those produced by conventional block-by-block georeferencing, and the findings are interpreted in relation to control-point distribution, tie-point geometry, transformation model, and historical sheet distortion.

The source data consisted of field-surveyed points corresponding to features that could be identified confidently both on the cadastral sheets and on the ground. Examples of such features include cadastral crosses, iron corner monuments, stone-wall corners, and other fixed features along property boundaries. The points were used first to provisionally georeference each sheet within GIS; their coordinates were then exported from the Link Table and used to classify each point as either a boundary point—located on the outer edge of a block or on a boundary shared with an adjacent block—or an internal point located within the block interior. This labeling scheme provided the basis for programmatically identifying shared-boundary relationships and assigning Ground Control Point and Ground Check Point roles before the data were imported into the application.

The full mathematical derivation of the constrained least-squares model and its matrices is not repeated here because it was presented in Chapter 4. Equations are included only where needed to interpret the implementation and accuracy measures. The discussion is structured around five interrelated issues: positional accuracy, independent Check Point performance, tie-point residuals, boundary continuity, and preservation of parcel geometry and area.

5.2 Objectives of the Practical Application

The practical application was intended to generate adjusted coordinates that agree as closely as possible with the field observations while maintaining continuity along the common boundaries of adjacent blocks. It therefore integrates the available geometric evidence within a single model rather than adjusting each sheet independently and attempting to correct gaps and overlaps afterward.

Table 5.1. Application objectives and the indicators used for verification.

Objective	Verification Indicator
Reference the historical cadastral block sheets to the adopted coordinate system	RMSE and coordinate differences at GCPs and independent check points
Maintain spatial continuity between adjacent cadastral blocks	Coordinate discrepancies at shared boundary vertices using Control Tie residuals and independent Check Tie Point comparisons before and after adjustment
Minimize inconsistencies along shared block boundaries	Reduction in positional mismatch between corresponding shared boundary points
Reduce local geometric distortion within individual blocks	Magnitude and spatial distribution of residuals after adjustment
Preserve the original cadastral geometry as far as practicable	Comparison of parcel boundaries, shapes, and areas before and after adjustment
Evaluate the overall quality of the adjusted solution	RMSE, residuals, Ground Check Point accuracy, Check Tie Point RMSE, Control Tie residuals, and visual GIS overlay inspection

5.3 Input Data and Software

The application used scanned paper sheets, coordinates of field-surveyed points, digital layers created during digitization and preliminary georeferencing, and coordinate tables exported from GIS. The MapGeoref application developed as part of this study was used to manage blocks and points, identify shared points, assemble the adjustment data, execute the connected least-squares solution, display the results, and save the project for later review or continuation.

Table 5.2. Principal inputs and their roles in the practical application.

Input	Description	Use
Scanned paper sheets	Digital images of the historical cadastral sheets	Source-coordinate measurement and boundary digitization
Field-surveyed points	Coordinates of stable features observed in the field	Ground control, independent checks, and reference-system connection
Link Table	Source and map coordinates for each georeferencing link	Input-file preparation and match verification
Digitized block boundaries	Parcel vertices, parcel lines, and block boundaries	Shared-point identification and continuity checking
MapGeoref application	Project-management and adjustment interface developed in this study	Simultaneous solution and result analysis

5.3.1 Study Area and Dataset Size

The final application covered six interconnected cadastral blocks in Tammun: Blocks 51, 53, 54, 56, 57, and 58. The simultaneous adjustment and all numerical results reported in this chapter are restricted to these six blocks. They were selected because they form a contiguous cadastral fabric for which historical sheets, field observations, and a sufficient set of common relationships were available to test the proposed method.

Final Six-Block MapGeoref Project – Audited Saved State					
Project format v3 · 902 stored records · 540 enabled Control Points · 166 ground Check Points					
Block 51	Block 53	Block 54	Block 56	Block 57	Block 58
Stored records 78	Stored records 177	Stored records 172	Stored records 189	Stored records 191	Stored records 95
Parcels 37	Parcels 79	Parcels 64	Parcels 113	Parcels 83	Parcels 54
Area (dunum) 1,328.2	Area (dunum) 1,408.0	Area (dunum) 1,340.0	Area (dunum) 1,056.0	Area (dunum) 1,107.0	Area (dunum) 1,043.3
Control Points 43	Control Points 108	Control Points 94	Control Points 135	Control Points 111	Control Points 49
Ground checks 20	Ground checks 31	Ground checks 30	Ground checks 33	Ground checks 32	Ground checks 20
Control Tie occ. 12	Control Tie occ. 34	Control Tie occ. 43	Control Tie occ. 18	Control Tie occ. 41	Control Tie occ. 22
Check Tie occ. 3	Check Tie occ. 4	Check Tie occ. 5	Check Tie occ. 3	Check Tie occ. 6	Check Tie occ. 3
Shared-point pool: 99 identifiers = 85 Control Tie groups + 12 Check Tie groups + 2 singleton identifiers Effective inter-block relationships = 97. Only the 85 Control Tie groups enter the simultaneous equations; the 12 CTP groups remain excluded for validation.					
Total parcels = 430 · Approximate area = 7,282.5 dunums					

Figure 5.1. Audited final state of the six-block MapGeoref project. The figure summarizes the records and point roles stored in the supplied .mapgeoref project (version 3). Source: prepared by the researcher from the final MapGeoref project file.

The supplied final project contains 902 stored point records across the six blocks. The distribution is 78 records in Block 51, 177 in Block 53, 172 in Block 54, 189 in Block 56, 191 in Block 57, and 95 in Block 58. The project role audit identified 540 enabled Ground Control Points and 166 independent Ground Check Points. The shared-point pool contains 99 identifiers: 85 effective Control Tie groups used in the simultaneous solution, 12 Check Tie Point (CTP) groups excluded from the equations for independent inter-block validation, and two singleton identifiers (TP5 and TP45) that contain only one occurrence and therefore create no inter-block condition. The parcel and area values remain those

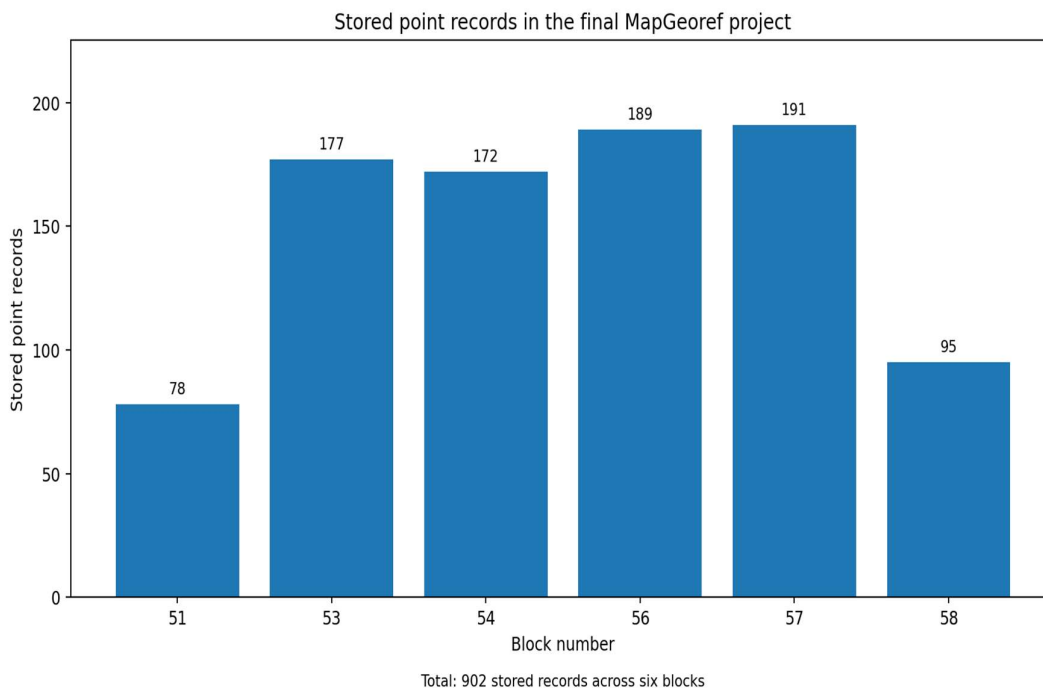
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documented from the cadastral dataset: 430 parcels covering approximately 7,282.5 dunums, including 79 parcels in Block 53 with an area of 1,408.013058 dunums.

Table 5.3. Updated summary of the six cadastral blocks in the final MapGeoref project; stored-record counts were audited directly from the supplied .mapgeoref file.

Block No.	Block Name	Stored Point Records	Parcels	Approximate Area (dunum)
51	Ras Al-Jarin	78	37	1,328.2
53	Tammun – Block 53	177	79	1,408.0
54	Abu Unaiz	172	64	1,340.0
56	Al-Sinka	189	113	1,056.0
57	Hamsa	191	83	1,107.0
58	Marah Eid	95	54	1,043.3
Total for the Six Blocks	–	902	430	7,282.5

As shown in Table 5.3, Block 57 contains the largest number of stored point records (191), followed by Block 56 (189) and Block 53 (177). These record counts represent the final saved project state and should not be interpreted as a direct measure of solution strength. Solution stability depends on the role, reliability, and spatial distribution of the observations and on the geometry of the Control Tie network.



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Figure 5.2. Distribution of the 902 stored point records by cadastral block in the final MapGeoref project. Source: prepared by the researcher from the supplied .mapgeoref file.

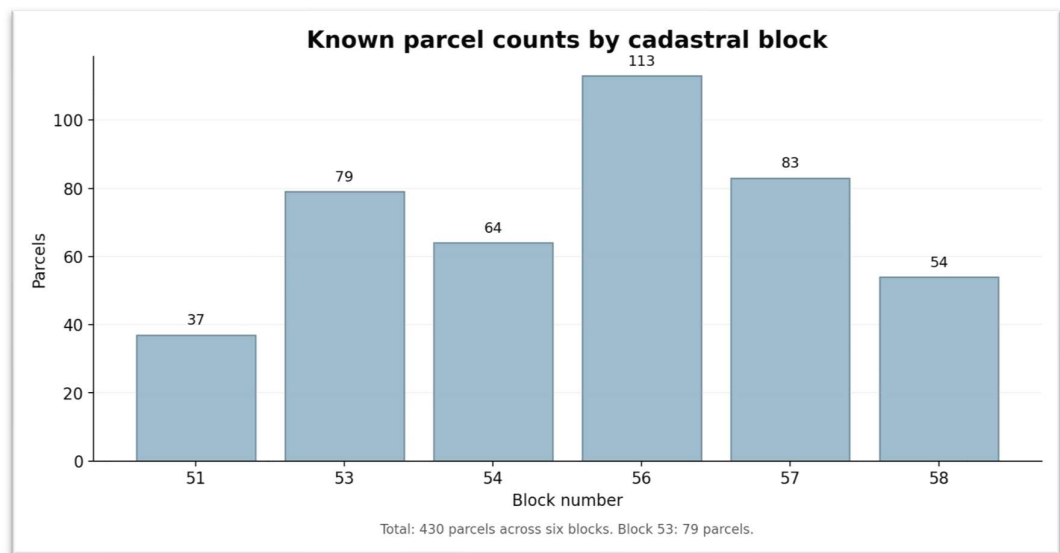


Figure 5.3. Number of parcels by cadastral block. Source: prepared by the researcher from the fieldwork reports.

Figures 5.2 and 5.3 show that stored point records and parcel counts vary among the six blocks. The final project contains 902 records, but a stored record is not automatically used in parameter estimation. The application distinguishes enabled Ground Control Points, independent Ground Check Points, Control Tie occurrences, Check Tie occurrences, and the two singleton tie occurrences. Block 53 contains 79 of the 430 parcels and 177 stored point records.

5.4 Overall Workflow

The work was conducted as a linked sequence of stages. An error in point identification or coordinate transcription at an early stage can propagate into the final solution, so data preparation was considered a central quality-control task rather than a routine preliminary step.

Table 5.4. Practical workflow from field identification to final GIS verification.

Stage	Principal Action	Output
1	Identify observable features on the sheets and in the field	Initial list of candidate points
2	Survey the candidates and verify their stability and clarity	Reliable field coordinates
3	Georeference each block provisionally in GIS	Georeferenced raster and Link Table
4	Export, classify, and verify point identifiers	Boundary, internal, and shared points
5	Assign GCP and Check Point roles and prepare input files	Standardized input file for each block

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Stage	Principal Action	Output
6	Load the blocks and define shared-boundary relationships	Connected project ready for adjustment
7	Assemble and solve the connected least-squares normal system; review residuals and validation results	Adjusted transformation parameters and quality indicators
8	Return the results to GIS and complete the final checks	Final layers and comparison tables

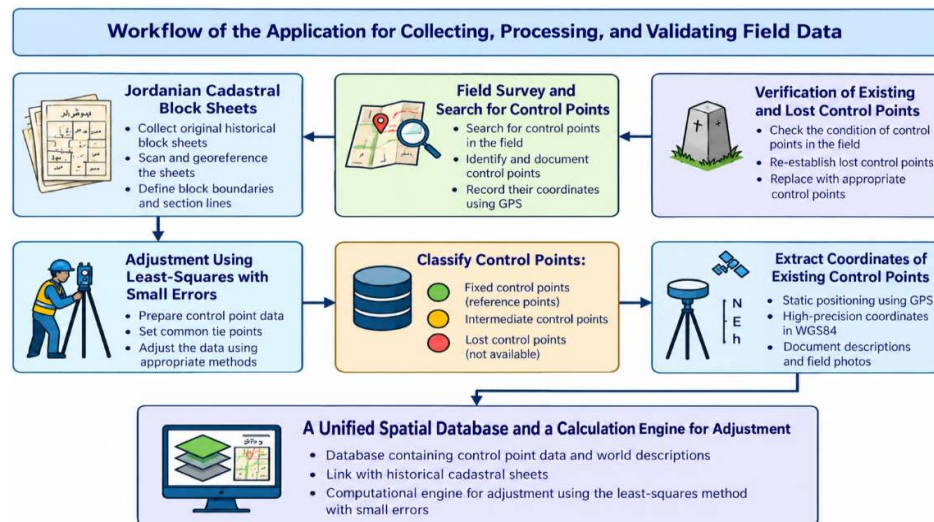


Figure 5.4. Workflow for collecting, validating, and preparing the field data for adjustment. Source: prepared by the researcher.

5.5 Collection and Preparation of Field-Surveyed Points

5.5.1 Selection of Field Features

Fieldwork began with the identification of features that could be recognized unambiguously on both the paper sheets and the ground. Candidate features included historical cadastral crosses, iron corner monuments, stone-wall corners, boundary intersections, and other marks that had remained stable over time. Visibility on the sheet alone was insufficient: a feature also had to be physically stable, well defined, and unaffected by recent reconstruction, displacement, or damage.

The spatial distribution of the points was also important. A cluster on one side of a block may provide a good local fit while leaving the remainder of the sheet dependent on weak extrapolation. Points were therefore distributed around the block perimeter and, where possible, throughout the interior. Special attention was given to locations shared by two or more blocks because these locations directly influence continuity of the cadastral fabric.

5.5.2 Field Survey and Verification

The selected features were surveyed using appropriate instruments and tied to the coordinate reference system adopted for the study. Each point was assigned a unique

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identifier and documented with a short description, feature type, related block or blocks, and notes on condition and suitability. These records reduced the risk of misidentifying nearby points and enabled uncertain features to be excluded before the adjustment was performed.

After the survey, the data were screened for transcription errors, outliers, and unintended duplicates. Approximate geometric relationships between points were also compared with their configuration on the historical sheets. A discrepancy did not necessarily indicate an error in the field survey because distortion may have existed in the source sheet; however, a large or implausible discrepancy required the field notes to be checked before processing continued.

Table 5.5. Recommended fields for documenting field-surveyed points.

Recommended Field	Recorded Content
Point_ID	Unique identifier not repeated across the project files
Easting / X Map	Observed easting coordinate
Northing / Y Map	Observed northing coordinate
Feature_Type	Cross, iron corner, wall corner, boundary mark, etc.
Block_ID	Block number or numbers associated with the point
Point_Role	GCP, check point, or tie point
Status	Accepted or excluded after verification
Remarks	Field condition and any information affecting reliability



(a) Survey pole centered on the mark



(b) Delineated and painted rock mark

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(c) English nail fixed in rock



(d) Cross cut into rock

Figure 5.5a. Selected field features verified in Block 51. Source: photographs taken by the researcher. The Block 51 photographs show the transition from visually identifying a surviving mark to positioning the survey pole over it for observation. They include crosses and rock marks with varying degrees of clarity. The photographs were used to verify that each coordinate referred to the intended sheet feature and to document its physical condition and setting before each point was designated as a control or check point.

Figure 5.5b. Selected field features verified in Block 58. Source: photographs taken by the researcher. The photographs of Block 58 illustrate the field conditions encountered, ranging from clear rock marks to features in stony or agricultural settings and a visible iron monument. This documentation also supported the assessment of each point's reliability, the differentiation between stable marks and those requiring further review, and the preservation of a visual record for interpreting residuals or rechecking a point against the historical sheet.

Hierarchy of Spatial Reference Markers for Real Estate Maps		
Marker Type	Reliability Level	Use in Least-Squares Adjustment
 Fixed Control Point (Existing and available)	 High reliability	 Strong control point Used directly in the least-squares adjustment.
 Intermediate Control Point (Movable or variable)	 Medium reliability	 Use with caution or with lower weight Requires additional verification before use.
 Lost Control Point (Not available)	 Low reliability	 Not used as control Mentioned only in historical records.
 Unknown/Unreachable Location (Information not confirmed)	 Reliability unknown	 Requires field verification or direct support Cannot be used currently in the adjustment.
This classification prevents misinterpretation and ensures consistent treatment of all historical markers, regardless of their reliability level in the least-squares adjustment.		

Figure 5.6. Evidence hierarchy used to classify the condition and reliability of cadastral marks. Source: prepared by the researcher.

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Using the hierarchy in Figure 5.6, marks were classified as preserved, disturbed, missing, inaccessible, or inconsistent in type between the sheet and the field. Preserved marks provided the strongest control evidence, whereas disturbed marks were treated more cautiously. Missing marks were not used as control points, but their records were retained to document the absence of field evidence.

5.5.3 Field-Access Constraints

In several blocks, some areas could not be accessed directly because of greenhouses, roads, wadis, physical obstructions, or field conditions. These areas were identified from aerial imagery rather than through an automatic classification of locations where cadastral marks were absent. This distinction is important: an uninspected location remains unresolved, whereas a missing mark indicates that the location was inspected but the feature was not found.



Figure 5.7. Example of an area with restricted access during the Block 51 field campaign. Source: Tammun Settlement Project, Phase II reports.

5.6 Preliminary Georeferencing of the Block Sheets in GIS

5.6.1 Loading the Sheet and Defining the Coordinate Reference System

Each scanned sheet was imported into GIS and assigned the same coordinate reference system used for the field survey. The units and ordering of the X and Y coordinate fields

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were checked explicitly. In the study files, X represents easting and Y represents northing. For coordinate values to be compared meaningfully, the reference system, axis order, and units must be consistent.

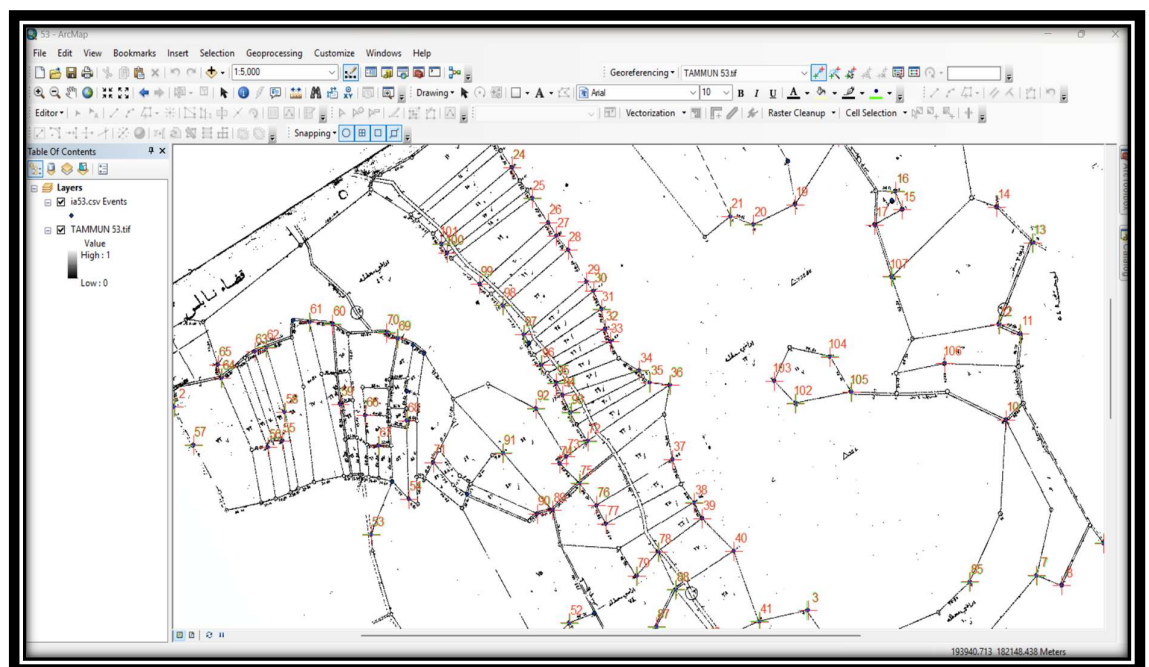
5.6.2 Entering Control Links

For each point surveyed in the field, the corresponding feature was located on the scanned sheet. This produced a pair of coordinates in the image system (X Source, Y Source) and a corresponding pair in the map system (X Map, Y Map) derived from the field survey. These coordinate pairs were entered into the Georeferencing tool, and each point identifier was checked before proceeding to the next observation.

At this stage, georeferencing served two functions: placing each sheet approximately in its correct spatial position and creating a structured coordinate table for transfer to the developed application. The independently transformed sheet was not treated as the final result because improving one block in isolation does not necessarily ensure agreement with its neighbor along their common edge. Therefore, the original source coordinates and surveyed map coordinates were preserved.

5.6.3 Checking the Preliminary Georeferencing

Once the links were entered, their spatial distribution, the initial residuals, and the position of the image relative to the reference data were analyzed. One point with a relatively large residual was flagged for review—not deleted automatically. The review checked the clicked position on the sheet, point identifier, X–Y ordering, decimal notation, and coordinate units.



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Figure 5.8. Distribution of georeferencing links across the Block 53 sheet in ArcMap. Source: screenshot prepared by the researcher.

5.7 Exporting and Organizing the Link Table Data

After preliminary georeferencing, the Link Table for each block was exported. At a minimum, the table contained the point identifier, source-image coordinates, and map coordinates derived from the field survey. The records were then organized in separate tables or in a single file sorted by block number. All numerical values were retained at full precision, and no premature rounding was applied.

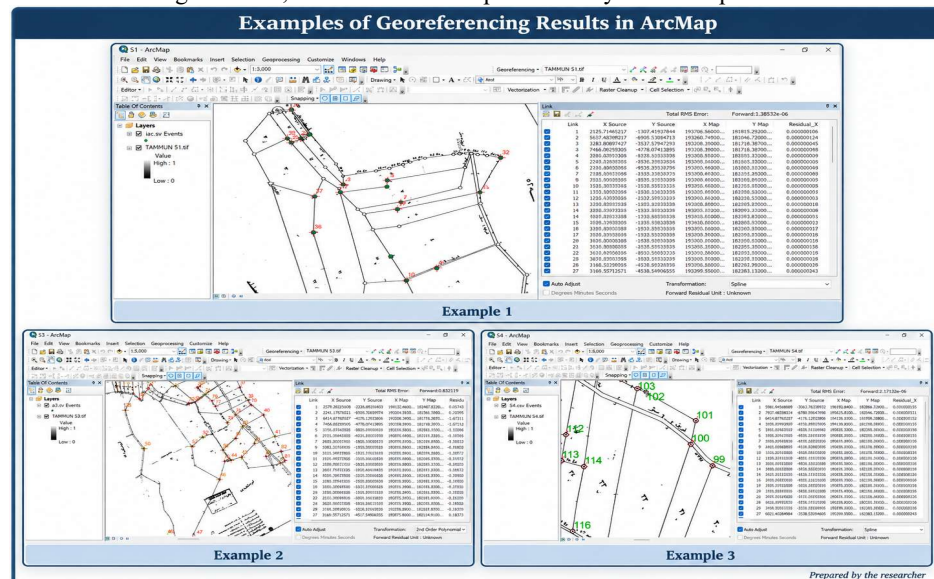
To illustrate the Link Table structure, one record from each of the Block 51, 53, and 54 files is shown in Table 5.6. In each case, the first record (Link = 1) was selected. The three rows are illustrative only and do not represent the full block datasets or the number of points used in the final adjustment. X Map and Y Map are the field-derived easting and northing coordinates in meters, whereas X Source and Y Source remain in the image coordinate system. For readability, the source coordinates are shown to five decimal places, although full precision was retained in the calculation files.

Table 5.6. Illustrative Link Table records: one point from each of Blocks 51, 53, and 54.

Block	Old Point	Link	X Source	Y Source	X Map (m)	Y Map (m)
51	116	1	2125.71265	-1307.41458	193706.556	181015.392
53	146	1	2579.82253	-2226.89254	194132.645	182467.823
54	128	1	5404.14546	-7862.70539	194807.848	182685.295

Figure 5.9 shows the Link Table windows for Blocks 51, 53, and 54. Spline transformations are shown in the screenshots for Blocks 51 and 54, while Block 53 shows a second-order polynomial transformation.

The residuals displayed in the screenshots therefore correspond to the preliminary georeferencing represented by each view and should not be interpreted as results of the final simultaneous adjustment. The figure illustrates the working interface, whereas Table 5.6 presents only one example record for each block.



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Figure 5.9. Link Table views for Blocks 51, 53, and 54 during preliminary georeferencing in ArcMap. The Block 53 view reports a Forward RMS of 0.832119 for the second-order polynomial case. Source: screenshots prepared by the researcher.

Before the tables were imported into the application, the data were checked for duplicate identifiers, blank cells, text values in coordinate columns, unexpected signs, inconsistent decimal precision, and points with nearly identical map coordinates but different identifiers. Similar records in adjacent-block files were also compared to determine whether they represented the same shared cadastral vertex.

5.8 Point Classification and Roles in the Adjustment

5.8.1 Boundary Points

Boundary points lie on a block boundary or along an interface between two adjacent blocks. The same cadastral vertex may appear on more than one sheet with different source-image coordinates, but all representations should refer to the same ground position after adjustment. These points are therefore central to the network adjustment and are used to impose inter-block coincidence conditions and reduce discontinuities when the sheets are assembled.

Figure 5.10 shows part of the junction between two adjoining sheets, where corresponding vertices and lines were compared to identify and review candidate shared-boundary points.



Figure 5.10. Detail of adjoining sheet boundaries used to review corresponding boundary features. Source: image prepared by the researcher.

5.8.2 Internal Points

Internal points are located within the block perimeter and provide additional control over distortion within the sheet. They supplement boundary control and improve the ability of

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the transformation to represent irregular distortion caused by manual drafting, paper shrinkage or expansion, scanning, and digitization. If an internal point was observed and verified in the field, it could be used either as a GCP or withheld from parameter estimation as an independent Check Point.

Figure 5.11 shows numbered georeferencing links at internal parcel vertices for Block 53. The enlarged view shows the location of each point identifier on the sheet and thus allows a better evaluation of the distribution of internal points.

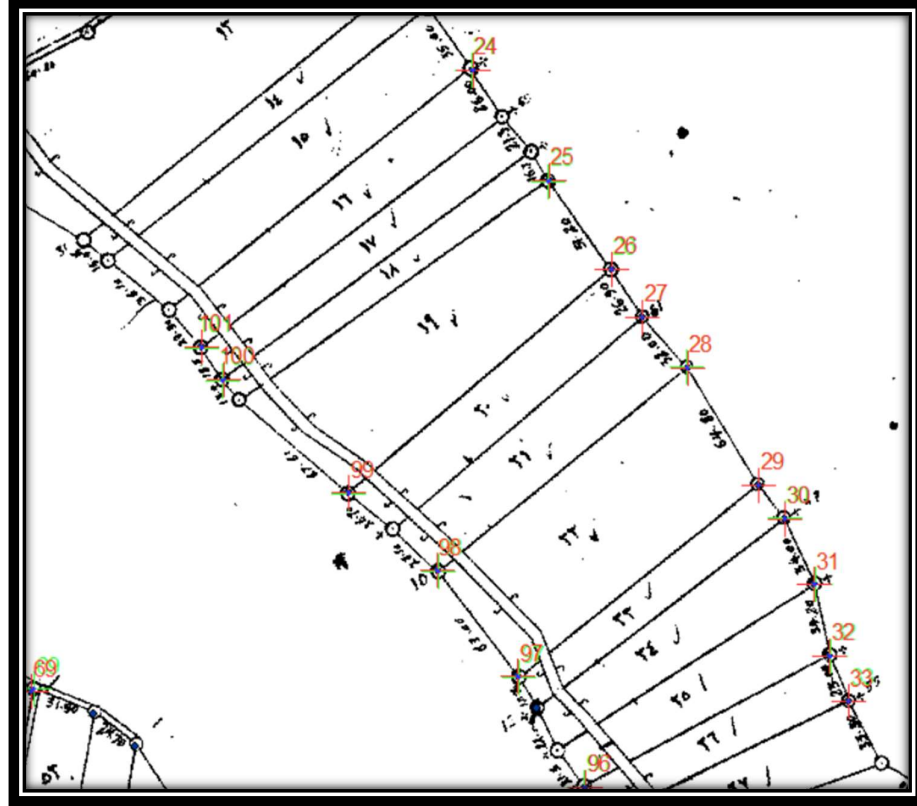


Figure 5.11. Enlarged view of georeferencing links at internal parcel vertices in Block 53. Source: image prepared by the researcher.

5.8.3 Points Shared by Adjacent Blocks

Boundary points were matched between block files using their identifiers, coordinates, and geometric positions along the common boundary. Identifiers alone were not considered sufficient because local numbering may be repeated or may vary among files. When two or more representations were determined to correspond to the same cadastral feature, they were assigned a common identifier and used to formulate a condition requiring their transformed coordinates to coincide.

If point p is represented in Blocks i and j , the continuity condition can be written in simplified form as follows:

$$X_i(p) - X_j(p) = 0, \quad Y_i(p) - Y_j(p) = 0 \quad (5.1)$$

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Equation (5.1) requires the two transformed representations of the shared point to occupy the same position. When a vertex is shared by more than two blocks, all relevant block representations enter the same connected adjustment system.

5.8.4 Division into Control and Check Points

The field-surveyed points were divided into two groups. GCPs were used to estimate the transformation parameters and anchor the adjustment, whereas Check Points were excluded from parameter estimation and used for independent testing of predictive performance. Both groups were spatially distributed; Check Points were not clustered in a single area, and each block retained sufficient GCPs for the selected transformation model. This separation prevents model evaluation from relying solely on points used for fitting. GCP residuals can be small despite substantial distortion elsewhere, so performance at independent check points provides a more conservative assessment of model suitability. An analogous separation is applied to shared points: Control Tie Points are used in the simultaneous boundary constraints, whereas Check Tie Points are withheld and used only to evaluate relative agreement between neighboring blocks.

نقاط التثبيت 53									نقاط التثبيت 53								
Old point	Link	X Source	Y Source	X Map	Y Map	Residual_x	Residual_y	Residual	Old point	Link	X Source	Y Source	X Map	Y Map	Residual_x	Residual_y	Residual
146	1	2579.82252808	-2226.89254003	194132.64500000	182467.82300000	-0.00000840	-0.00000800	0.00001160	6	3	6414.87760287	-4178.12935806	194184.91800000	181559.33800000	-0.00000493	-0.00000459	0.00000680
1007	2	2241.17870021	-8128.36059794	193024.55100000	181906.50400000	0.00000029	-0.00000011	0.00000031	1038	8	7349.95443086	-2131.28264903	194649.62900000	181601.69600000	-0.00001082	-0.00001038	0.00001499
1011	4	7466.08529305	-4778.04413895	194184.65600000	181303.47000000	-0.00000522	-0.00000508	0.00000728	163	10	5953.03172484	-1884.98408123	194547.39500000	181884.19400000	-0.00000991	-0.00000943	0.00001368
1012	5	7526.67145492	-4667.19387715	194211.52300000	181303.76700000	-0.00000550	-0.00000534	0.00000766	1045	12	5258.68628865	-1552.81626798	194535.18100000	182046.72000000	-0.00001041	-0.00000989	0.00001436
1013	6	7495.68873866	-4310.84139024	194272.64400000	181346.32700000	-0.00000607	-0.00000586	0.00000844	1047	14	4426.47822532	-1096.22439350	194530.92000000	182246.21400000	-0.00001151	-0.00001096	0.00001590
1039	7	7172.41976269	-2281.2604147	194603.84900000	181619.22600000	-0.00001015	-0.00000973	0.00001406	177	15	4035.64329720	-1826.76142277	194357.41900000	182242.01600000	-0.00000922	-0.00000874	0.00001270
1041	9	7233.29036579	-1638.81146698	194726.73900000	181673.70800000	-0.00001208	-0.00001159	0.00001674	148	18	3253.17861829	-2020.28866678	194241.09600000	182365.22900000	-0.00000873	-0.00000828	0.00001204
1044	11	5413.31788888	-1428.83533374	194573.54100000	182230.68700000	-0.00001088	-0.00001035	0.00001501	150	19	3535.07643282	-2622.75666208	194161.09300000	182250.67500000	-0.00000705	-0.00000666	0.00000970
1046	13	4827.44377566	-970.61010385	194596.98800000	182185.55500000	-0.00001204	-0.00001148	0.00001664	152	21	3340.06059913	-3160.49586754	194042.56400000	182230.94700000	-0.00000576	-0.00000543	0.00000791
176	16	3877.79472520	-1804.66458955	194345.32400000	182272.87400000	-0.00000928	-0.00000880	0.00001279	145	22	2532.04888868	-2542.89539416	194070.25000000	182443.03000000	-0.00000758	-0.00000720	0.00001045
167	17	4022.18544331	-2098.64516460	194307.02500000	182216.50000000	-0.00000844	-0.00000799	0.00001162	56	25	2350.64768808	-4592.63988380	193679.57300000	182261.70300000	-0.00000318	-0.00000305	0.00000441
151	20	3497.1609638	-3022.57518055	194084.81000000	182216.77900000	-0.00000606	-0.00000571	0.00000833	54	27	2716.50960561	-4558.14275372	193724.38100000	182197.89700000	-0.00000307	-0.00000292	0.00000424
142	23	2130.45964815	-3899.03171871	193781.37800000	182373.99700000	-0.00000463	-0.00000442	0.00000640	52	29	3169.55712571	-4517.54809635	193779.80600000	182118.91700000	-0.00000301	-0.00000284	0.00000414
59	24	2047.78689731	-4619.10619670	193643.21000000	182313.68000000	-0.00000332	-0.00000320	0.00000461	50	31	3424.33331237	-4517.06529361	193806.46000000	182072.32600000	-0.00000297	-0.00000279	0.00000408
55	26	2590.33577893	-4567.34112219	193709.51300000	182220.19600000	-0.00000311	-0.00000297	0.00000430	48	33	3686.71340899	-4581.04790876	193822.45200000	182017.51500000	-0.00000284	-0.00000267	0.00000389
53	28	2863.23186651	-4526.66128718	193745.66400000	182174.12100000	-0.00000307	-0.00000292	0.00000424	44	35	4148.00071100	-4451.49619691	193895.60900000	181946.75600000	-0.00000310	-0.00000290	0.00000425
51	30	3262.15671419	-4503.55881188	193792.38000000	182103.37100000	-0.00000301	-0.00000284	0.00000414	38	38	5174.15581119	-4600.29683053	193976.26600000	181742.68800000	-0.00000320	-0.00000301	0.00000439
49	32	3578.60685369	-4565.97952134	193813.40000000	182038.83300000	-0.00000287	-0.00000270	0.00000394	13	40	5685.85489479	-4493.94767335	194049.59500000	181660.16700000	-0.00000371	-0.00000351	0.00000510
46	34	4019.32150225	-4481.43684632	193875.78900000	181967.89700000	-0.00000303	-0.00000284	0.00000415	11	42	6221.49435741	-5084.85116402	194009.59700000	181500.28000000	-0.00000321	-0.00000308	0.00000445
43	36	4248.35258433	-4307.56912948	193932.48900000	181943.08500000	-0.00000338	-0.00000316	0.00000463	1003	43	6355.44819538	-5515.54360087	193934.67100000	181430.10200000	-0.00000274	-0.00000267	0.00000382
40	37	4779.04925818	-4587.05792581	193937.01100000	181816.81700000	-0.00000304	-0.00000285	0.00000416	1002	44	6293.49545917	-5764.46785351	193883.37200000	181414.74200000	-0.00000236	-0.00000232	0.00000331
37	39	5319.19451516	-4603.06079483	193991.17600000	181716.08400000	-0.00000328	-0.00000309	0.00000450	1001	45	6250.51559930	-5908.73125481	193852.94800000	181408.03700000	-0.00000214	-0.00000213	0.00000302
7	41	6284.57702387	-4587.69327353	194096.17600000	181540.25800000	-0.00000407	-0.00000388	0.00000562	1035	47	7615.95103112	-7435.87992758	193721.41900000	180996.22200000	-0.00000257	-0.00000282	0.00000382
1000	46	6595.54566618	-6239.29411378	193829.74600000	181309.00900000	-0.00000215	-0.00000218	0.00000306	1033	48	7564.04185492	-7739.96949008	193681.87400000	180973.89400000	-0.00000233	-0.00000263	0.00000352
1032	49	7257.45080131	-7976.95794043	193586.83700000	181005.23400000	-0.00000178	-0.00000211	0.00000276	21	50	5078.00330646	-7299.97595574	193476.05000000	181475.03000000	-0.00000001	-0.00000018	0.00000018
23	52	5471.61686274	-6033.65487093	193747.71800000	181538.22300000	-0.00000135	-0.00000135	0.00000190	22	51	5551.52539703	-6365.48251200	193696.81900000	181489.06400000	-0.00000105	-0.00000110	0.00000152
1027	53	3989.46474622	-7168.18514057	193384.71300000	181687.88300000	0.00000027	0.00000008	0.00000028	126	55	2950.28996946	-7456.91395028	193221.77300000	181848.61500000	0.00000034	0.00000007	0.00000034
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Figure 5.12. Division of the field-surveyed points into ground control points and independent check points. Source: prepared by the researcher.

Figure 5.12 illustrates the division of the field-surveyed observations into independent check points and GCPs used in parameter estimation.

5.9 Inter-Block Tie Points

5.9.1 Tie-Point Concept and Its Distinction from Control Points

In this study, a tie point is a relationship connecting the same cadastral feature on two or more adjacent sheets. A common boundary vertex can have one set of source-image coordinates in the first sheet and another in the second, while both occurrences refer to the same cadastral feature. A tie point therefore does not necessarily provide a new surveyed ground coordinate; it provides geometric connectivity between blocks after their respective transformations are applied.

A tie point is not a Ground Control Point (GCP). A GCP has known field coordinates in the adopted reference system and anchors a block directly to the ground. Shared points are further divided into Control Tie Points and Check Tie Points. Control Tie Points enter the simultaneous adjustment and enforce connectivity between blocks. Check Tie Points (CTPs) are excluded from parameter estimation and are used to assess the relative positional consistency between adjacent blocks independently. Ground Check Points remain a separate validation class because they have independent reference coordinates and assess absolute rather than inter-block accuracy.

Table 5.7. Point types and their roles in the adjustment and verification process.

Point Type	Available Information	Used in Estimation?	Role
GCP	Source coordinates and observed ground coordinates	Yes	Anchors the block in the reference system
Control Tie Point	Occurrences of the same shared point in two or more blocks	Yes—in the simultaneous adjustment	Enforces connectivity and transfers continuity information between blocks
Check Tie Point (CTP)	Occurrences of the same shared point deliberately withheld from the tie constraints	No	Provides independent relative validation of inter-block positional consistency
Check Point	Source coordinates and independent ground coordinates	No	Provides an external assessment of positional accuracy
Internal Point	Internal observation classified as either a GCP or a check point	According to its class	Controls or tests distortion within the block

5.9.2 Identification of Candidate Tie Points

Once the Link Tables were exported and the block boundaries digitized, tie-point identification began. Boundary points from each block were collected and compared with those of neighboring blocks. The application used point identifiers, coordinates, and spatial adjacency to identify candidates, but no match was accepted automatically before visual review in GIS. Numerical proximity alone did not establish that two records represented the same cadastral corner.

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A candidate was accepted as a tie point only when three conditions were satisfied: both representations lay on the correct common boundary, the topology of their connected lines matched, and neither their descriptions nor neighboring features indicated a conflict. When one vertex was shared by three blocks, all of its representations were recorded in a single tie group rather than as separate pairwise links that could introduce inconsistent conditions.

5.9.3 Tie-Point Coding in the Application Files

Each tie relationship was assigned a unique identifier, such as T001, while retaining the block number, local point identifier, and source coordinates of every occurrence. This structure preserves each original local identifier while informing the application that the records belong to one shared point. The principal fields were Tie_ID, Block_ID, Local_Point_ID, X Source, Y Source, boundary type, confidence class, and acceptance status.

Table 5.8. Illustrative structure for coding tie-point occurrences.

Tie_ID	Block_ID	Local_Point_ID	X_Source	Y_Source	Confidence	Status
CP 1	51	P-035	3230.740	6537.084	High	Accepted
CP_1	53	P-108	2241.179	8128.361	High	Accepted
CP_2	51	P-036	2132.667	4872.731	High	Accepted
CP 2	53	P-109	3989.465	7168.185	High	Accepted
CP 3	51	P-037	2660.537	1508.250	High	Accepted
CP_3	53	P-110	7257.451	7976.958	High	Accepted
CP 4	51	P-038	2400.607	1216.867	High	Accepted
CP_4	53	P-111	7564.042	7739.969	High	Accepted

The first two entries in Table 5.8 represent two occurrences of T001 in adjacent Blocks i and j. The source coordinates are not expected to be equal because each image has its own coordinate system and distortion; only the transformed coordinates after adjustment are required to coincide.

5.9.4 Computing the Coordinates of the Tie-Point Occurrences

The application applies the transformation selected for each block to the source coordinates of each tie-point occurrence. For an affine transformation, the coordinates of the occurrence in Block i are computed as:

$$X_i = a_1x_i + a_2y_i + a_3, \quad Y_i = b_1x_i + b_2y_i + b_3 \quad (5.2)$$

The corresponding occurrence in Block j is computed with the parameters and source coordinates of that block. Before correction, the tie-point misclosure vector is:

$$w_t = [X_i - X_j \quad Y_i - Y_j]^T \quad (5.3)$$

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The first component is the easting difference and the second is the northing difference. The planar separation before or after adjustment is calculated as:

$$d_t = \sqrt{[(X_i - X_j)^2 + (Y_i - Y_j)^2]} \quad (5.4)$$

A smaller d_t indicates closer agreement between the two representations. However, acceptance is based not only on numerical coincidence but also on satisfactory GCP and Check Point residuals, as well as the geometry of the adjoining boundaries.

5.9.5 Expressing Tie Points as Conditional Equations

In general, the conditions are:

$$f_x = X_i(x_i, y_i, \theta_i) - X_j(x_j, y_j, \theta_j) = 0 \quad (5.5)$$

$$f_y = Y_i(x_i, y_i, \theta_i) - Y_j(x_j, y_j, \theta_j) = 0 \quad (5.6)$$

where θ_i and θ_j are the transformation-parameter vectors for Blocks i and j . For the affine model, substitution places parameters from both blocks in the same row of the condition matrix. The easting condition, for example, is:

$$(a_{1i}x_i + a_{2i}y_i + a_{3i}) - (a_{1j}x_j + a_{2j}y_j + a_{3j}) = 0 \quad (5.7)$$

Equation (5.7) shows that a tie point does more than correct an isolated coordinate; it couples the transformation parameters of neighboring blocks. Because the tie network is connected, strong ground control in one block can influence neighboring blocks, and all transformation parameters are solved within a single system rather than through a sequence of independent transformations.

5.9.6 Simplified Tie-Point Example

Assume that, before the final adjustment, the application computes T001 in Block i as $X_i = 171000.42$ m and $Y_i = 118500.16$ m, and in Block j as $X_j = 170999.78$ m and $Y_j = 118500.55$ m. The misclosure components are then:

$$\Delta X = 171000.42 - 170999.78 = +0.64 \text{ m}$$

$$\Delta Y = 118500.16 - 118500.55 = -0.39 \text{ m}$$

$$d_t = \sqrt{(0.64^2 + 0.39^2)} \approx 0.75 \text{ m} \quad (5.8)$$

This value corresponds to an initial separation of approximately 0.75 m between two representations of the same vertex. The simultaneous adjustment distributes corrections through the parameters of both blocks rather than moving one occurrence entirely toward the other. If the post-adjustment components were $\Delta X = 0.03$ m and $\Delta Y = -0.02$ m, the remaining separation would be approximately 0.036 m. These values are illustrative only and are not part of the reported project results.

5.9.7 Validation of Tie Points

Before a tie point was included in the adjustment, both occurrences were verified as representations of the same feature on the correct common boundary. The final model used neither differential weights nor distance constraints; ties were accepted or rejected after geometric and visual examination. This step prevents an incorrect match from imposing artificial continuity between unrelated points.

After this geometric screening, the accepted shared points were assigned either a Control Tie role or a Check Tie role. The Control Tie subset was included in the shared-boundary equations. The CTP subset was retained in both adjoining sheets but excluded from the equations so that its transformed coordinates could be compared independently. The same CTP identifiers were maintained for the independent and simultaneous runs to ensure that the before-and-after comparison referred to exactly the same observations.

For each CTP, MapGeoref computes transformed easting and northing coordinates independently from the Block A and Block B transformations. The reported validation fields are X_A, Y_A, X_B, Y_B, X, Y, and the two-dimensional separation. The CTP report also summarizes RMSE_X, RMSE_Y, RMSE_2D, maximum separation, and percentage improvement from the independent to the simultaneous solution.

Tie-Point Status Classification and Required Actions

Tie Status	Description	Action
Accepted	Clear feature with consistent topology in both blocks	Include in the shared-boundary conditions
Review	Possible match whose identity remains uncertain	Recheck the sheets and field evidence
Rejected	Geometric conflict or incorrect identification	Exclude from the condition system

Table 5.9. Tie-point review status and corresponding action.

5.9.8 Using Tie Points in the Application

After the block files were loaded, the shared-point detection function displayed candidate tie groups. Each group was reviewed, erroneous links were edited or removed, and valid groups were assigned a role in the Ties panel. Control Ties remained active constraints in Solve All, whereas Check Ties remained enabled for reporting but were excluded from the normal-equation system. The developed MapGeoref interface provides a Check Tie tool, a role selector, a CTP Report, a before/after CTP Comparison View suitable for screenshot documentation, and CSV/HTML/Word-style academic reporting of the independent and simultaneous CTP statistics.

When a block has relatively few GCPs but is connected to well-controlled neighbors through reliable and well-distributed ties, the shared relationships can transfer reference-

system control into that block. Tie points, however, are not a substitute for field control. A well-connected network with insufficient external control can be internally consistent while remaining weak in absolute position.

5.9.9 Tie-Point Residuals and Acceptance Rules

After adjustment, each tie was checked for ΔX , ΔY , and d_t , and the records were ordered by descending planar residual to identify potential problems. A large residual triggered a review of point identity, clicked position, boundary type, and transformation model. The ties were also examined in GIS to confirm that a smaller numerical residual corresponded to improved continuity of parcel and boundary lines. For Control Tie Points, these values are in-solution residual diagnostics. For Check Tie Points, the same coordinate differences are external inter-block validation measures because the CTPs were not used to estimate the transformations.

No universal acceptance threshold can be defined independently of sheet scale, survey accuracy, and cadastral purpose. Acceptability was therefore judged in the context of the accuracy achieved in this study, together with the GCP residuals and the improvement observed across the entire interface. A tie with a large residual should not be removed automatically because it may reflect genuine local distortion or an error elsewhere in the connected network.

5.9.10 Effect of Tie-Point Distribution on Solution Stability

Tie points are most effective when they are distributed along the common boundary, including near its ends, rather than clustered in one area. A single tie provides local contact but is insufficient to constrain relative rotation or divergent behavior farther along the interface. Several well-spaced ties provide better control of the boundary as a whole. Three-block junctions can also strengthen network connectivity, provided that their identities are reliable and the imposed conditions are neither redundant nor contradictory.

Figure 5.23 presents the shared-point network extracted from the final project. It shows all 97 effective inter-block relationships; in the final validation configuration these are partitioned into 85 Control Tie groups used as constraints and 12 Check Tie groups retained outside the equations for validation.

5.10 Preparation of Application Input Files

After classification, a separate input file was created for each block. It contained source coordinates, field-derived map coordinates, point role, and point class. Column names and number formats were standardized, and the block identifier was checked for consistency across all records. Shared points were assigned common identifiers so that the application could recognize their occurrence in more than one block.

Table 5.10. Input-file validation checks and acceptance criteria.

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Check	Acceptance Criterion
Data completeness	No required coordinate is missing
Unique identifiers	No unintended duplicate occurs within a block
Correct X and Y fields	X is easting and Y is northing in a common unit
Shared-point definition	A common identifier refers to the same physical or cadastral feature
Spatial distribution	Points surround the block and represent its interior where possible
Check-point independence	Check points are excluded from transformation-parameter estimation
Numerical precision	Coordinates are not rounded early or converted to text

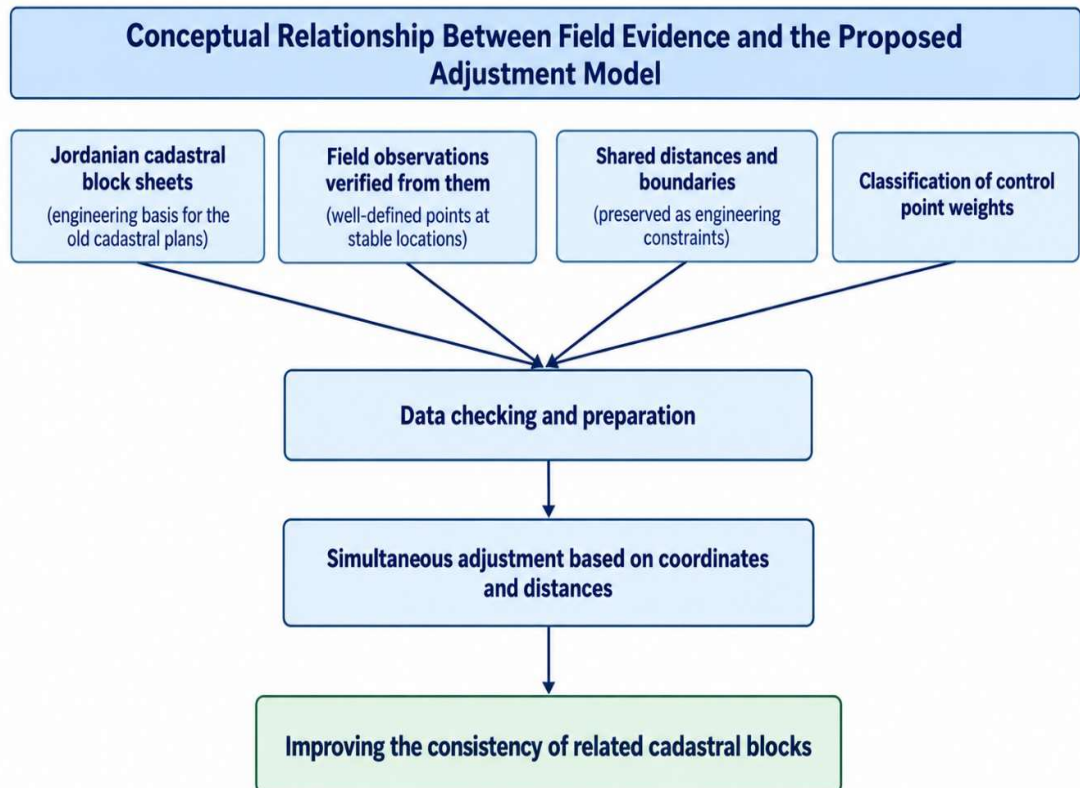


Figure 5.13. Relationship between field evidence and the proposed simultaneous georeferencing model.
Source: prepared by the researcher.

Figure 5.13 shows that the final solution depends on more than coordinates alone. Historical sheets, verified physical marks, GPS observations, geometric relationships, and reliability assessments provide complementary inputs to the mathematical model. The adjusted results are returned to GIS for positional validation and continuity checks. Together, these interfaces make simultaneous adjustment practical even when surviving field evidence is unevenly distributed among blocks.

5.11 Implementing the Adjustment in the Developed Application

5.11.1 Creating the Project and Loading the Blocks

In MapGeoref, a new project was created and the six block files were loaded and reviewed. The application saves projects with the .mapgeoref extension so that block data, point roles, transformation settings, fitted parameters, residual summaries, shared-point definitions, and validation results can be restored. The supplied project uses file-format version 3 and contains an internal save timestamp of 14 September 2026 (UTC). Its audited saved state

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contains Blocks 51, 53, 54, 56, 57, and 58; 902 total point records; 540 enabled Ground Control Points; 166 Ground Check Points excluded from estimation; and 99 shared-point identifiers. Of the shared identifiers, 85 two-occurrence Control Tie groups are used in the simultaneous equations, 12 two-occurrence Check Tie groups are withheld for independent validation, and TP5 and TP45 are singleton identifiers that form no inter-block equation. The final saved transformation state is third-order polynomial (Poly3). The Save Project/Ctrl+S and Open Project functions preserve this working state for later review.

Table 5.11. Audited contents and computational dimensions of the final MapGeoref project used for the reported adjustment.

Project Element	Value Audited from the Final Saved Project / Application
Project format	MapGeorefProject, version 3
Number of blocks	6
Total stored point records	902
Enabled Ground Control Points	540
Independent Ground Check Points	166
Shared-point identifiers	99
Control Tie groups used in equations	85
Check Tie groups excluded for validation	12
Singleton tie identifiers	2 (TP5 and TP45; no inter-block equation)
Final stored transformation	Third-order polynomial (Poly3)
Unknown transformation coefficients in Poly3 network	120 (20 parameters $\times$ 6 blocks)
Planar residual elements used in combined RMSE	625 (540 Control Points + 85 Control Tie relationships)
Coordinate-equation rows in the design matrix	1,250 (two coordinate rows per planar element)
Application redundancy indicator	505 (= 625 planar elements – 120 unknowns)

Figure 5.14a documents an earlier interface snapshot in which the Check class contained 166 points and an Overall Check RMSE 2D of 0.7940 was displayed. The final saved project still contains the same 166 independent Ground Check Points. Recalculation from the final full-network transformations gives overall Ground Check Point RMSE_{2D} values of 1.2015 m for Affine, 0.8001 m for Poly2, and 0.7884 m for Poly3.

The screenshot value is therefore retained as an interface snapshot, whereas the final numerical comparisons in this chapter are based on the audited project state and the reproducible final solution reports.

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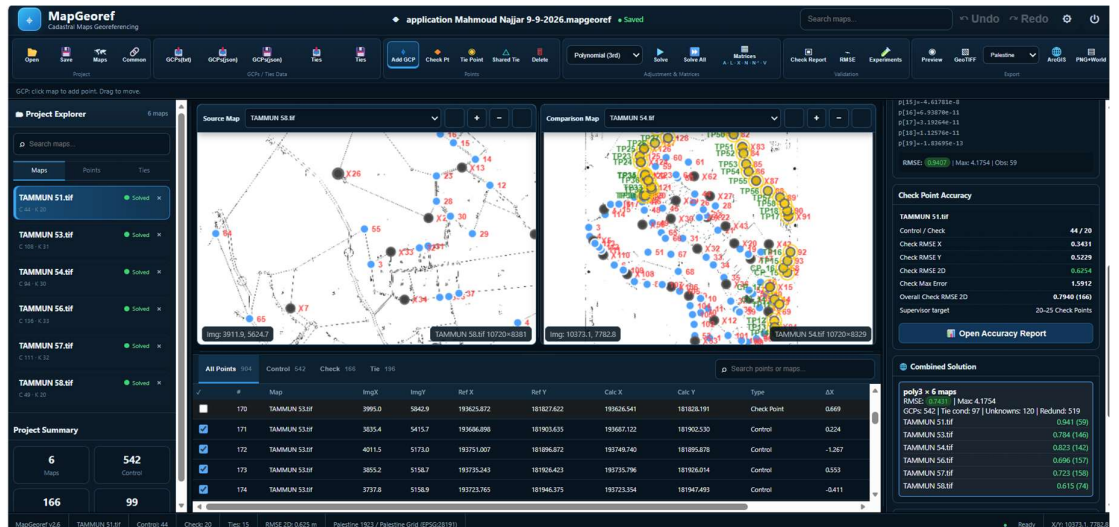


Figure 5.14a. MapGeoref interface showing the six blocks, point management, joint-solution summary, and the displayed Check Point accuracy panel. Source: screenshot supplied by the researcher.

5.11.2 Detecting and Reviewing Shared Points

The shared-point extraction tool clustered records that appeared in more than one block. Numerical proximity and geometric identity were then tested for each candidate cluster. Spatial proximity alone was insufficient unless the records represented the same cadastral corner. Valid matches were assigned a single relationship in the adjustment. After shared-point identity was confirmed, a subset could be deliberately withheld as CTPs; the remaining shared points functioned as Control Ties in the connected solution.

Figure 5.14b shows the Shared Tie tool with Block 58 in the source window and Block 51 in the review window. Identifiers such as TP80 can be viewed in both panels so that the user can confirm that the two occurrences represent the same shared cadastral feature before assigning a Control Tie or Check Tie role.

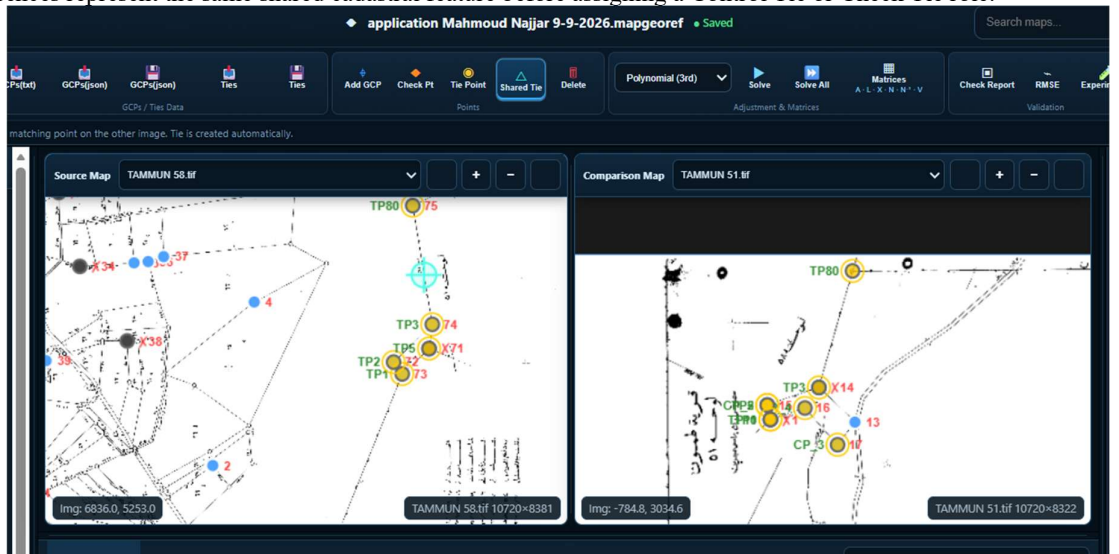


Figure 5.14b. Review of shared points between Blocks 58 and 51 using the Shared Tie tool in MapGeoref. Source: screenshot prepared by the researcher.

5.11.3 Selecting the Transformation Model

The transformation model was selected based on the number and spatial distribution of points and the nature of distortion within each sheet. Similarity transformations use relatively few parameters and preserve relative shape; affine transformations allow differential scale and shear; polynomial transformations provide increasing flexibility for representing local irregular distortion. Higher-order models are not necessarily better because excessive flexibility can overfit the GCPs and produce undesirable behavior between points. Model selection was therefore based on residuals, tie-point continuity, and available check information rather than on GCP residuals alone.

5.11.4 Defining the Shared-Boundary Conditions

Coincidence conditions on accepted Control Tie Points and shared boundaries were the only inter-block constraints in the final model. The model included neither differential weights nor distance constraints. Each Control Tie added an easting condition and a northing condition forcing its two transformed representations toward coincidence. Check Tie Points were deliberately excluded from these conditions and were reserved for independent inter-block validation after the transformations were estimated.

5.11.5 Forming the Simultaneous Solution

Once the inputs and tie roles have been checked, MapGeoref builds one connected design matrix A and observation vector L for all six blocks. Each enabled Ground Control Point contributes two coordinate equations. Each effective Control Tie group contributes an easting difference equation and a northing difference equation with a zero right-hand side, thereby coupling the transformation coefficients of the adjoining blocks. Check Tie groups and Ground Check Points remain outside the estimation system.

For the Affine, second-order polynomial, and third-order polynomial models used in the final experiments, the unknown transformation coefficients enter these equations linearly. The implemented solver therefore forms the normal matrix $N = A^T A$ and right-hand side $A^T L$ and solves the coefficients directly. No nonlinear iteration or successive parameter-update loop is used for these three implemented models. In the final Poly3 full-network run the system contains 120 unknown coefficients, 1,250 coordinate-equation rows, and 625 planar residual elements used by the application in its combined RMSE calculation.

$$\hat{x} = (A^T A)^{-1} A^T L \quad (5.9)$$

where $\hat{x}$ is the vector of transformation coefficients for all connected blocks, A is the assembled design matrix, and L contains the observed ground coordinates and the zero-valued Control Tie conditions. The direct solution reflects the actual implementation in

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MapGeoref for Affine, Poly2, and Poly3. The quality of that numerical solution must still be assessed through residuals, independent Ground Check Points, withheld CTPs, and GIS geometry.

5.11.6 Monitoring the Solution and Investigating Outliers

Residuals were checked by block and by point for each run. A large residual may result from a transcription error, an incorrect tie, a weak field feature, or genuine sheet distortion that the selected transformation cannot represent. Each case was therefore reviewed in a fixed sequence: the original record, the position of the record in GIS, the assigned role, and finally the suitability of the transformation model. An observation was not rejected solely because it increased the error statistic; exclusion required a documented reason. The CTP Comparison View provides an additional diagnostic by presenting the independent and simultaneous coordinate differences side by side for the same withheld shared point, which is useful for both numerical review and documented screenshots in the thesis.

MapGeoref project view: active GCPs, Ties, and final Poly3 results

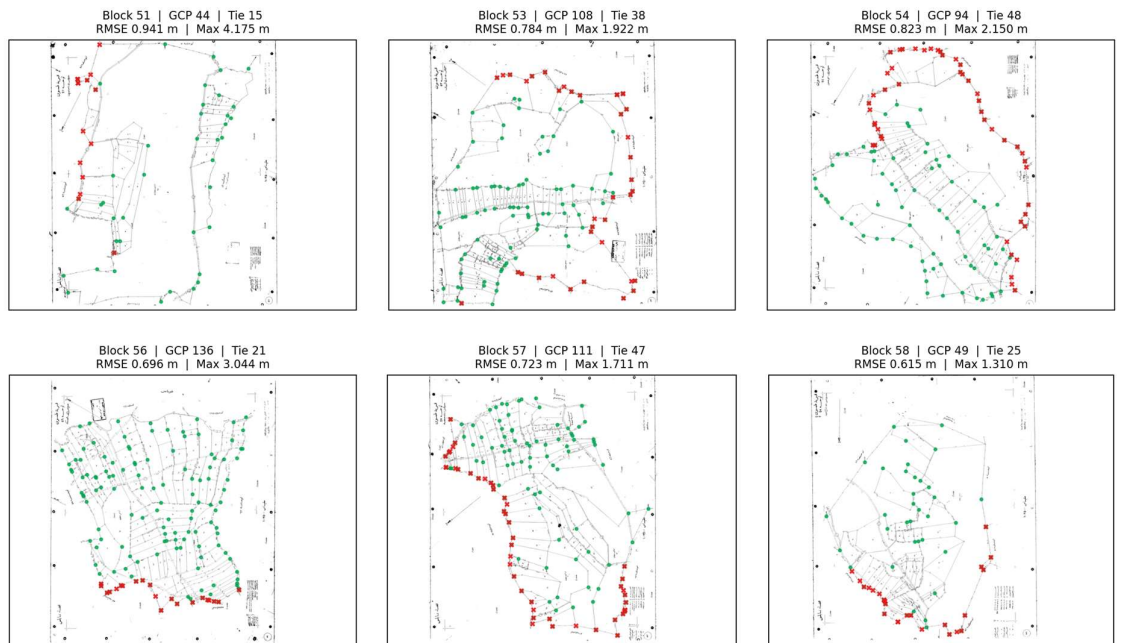


Figure 5.15. Restored project view showing active GCPs in green, tie-point locations in red, and the solution result for each block. Source: prepared by the researcher from data stored in MapGeoref.

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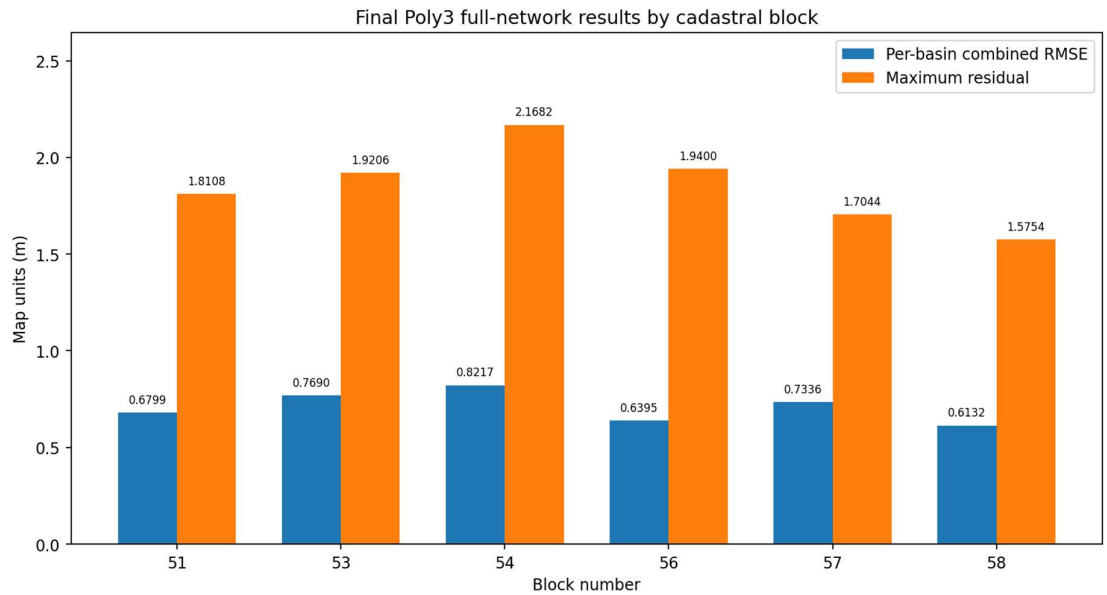
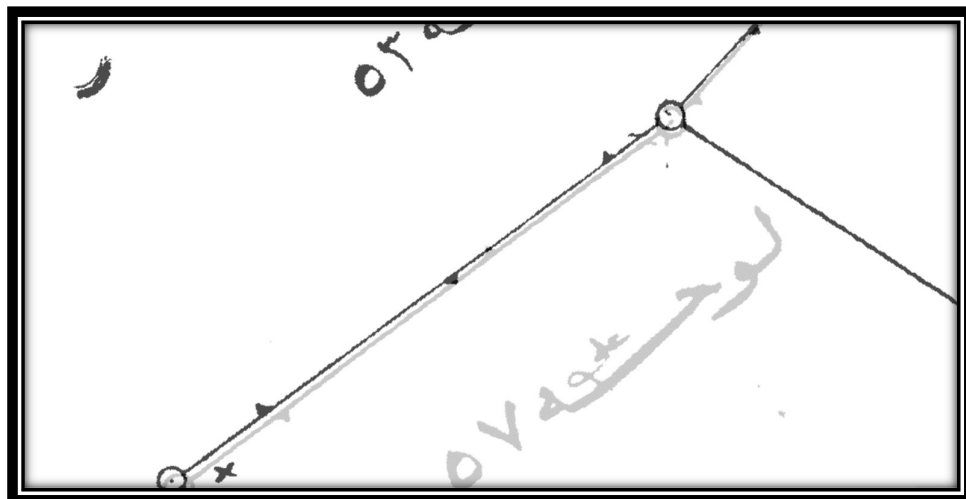


Figure 5.16. Per-block combined RMSE and maximum residual in the final Poly3 Full Network + CTP solution. The values are calculated from the final configuration of 540 Control Points and 85 Control Tie groups; 166 Ground Check Points and 12 Check Tie groups are excluded from estimation. Source: final MapGeoref project and solution calculations.

5.12 Returning the Adjusted Results to GIS

After accepting the solution, the adjusted coordinates, transformation parameters, and residual tables were exported back to GIS. This step enabled verification of the final spatial positions of the blocks and the continuity of their common boundaries. It also related the numerical output of MapGeoref to the final geometric behavior of the sheets when displayed together in a single GIS environment.

Blocks 53 and 57 in Tammun illustrate this verification stage. The two sheets were overlaid in ArcMap and their common interface was examined, with particular attention to the vertices and line segments defining the shared boundary. Figure 5.17 shows the two blocks before the final adjusted result from MapGeoref was applied.



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Figure 5.17. Blocks 53 and 57 displayed together in ArcMap for inspection of their common boundary before importing the final adjusted result. Source: screenshot prepared by the researcher.

The accepted shared vertices between the two blocks entered the boundary-conditioned adjustment as Tie Points or Shared Boundary Points. Following the simultaneous solution, the adjusted sheets were exported and reintroduced into GIS as separate georeferenced layers. Figure 5.18 shows the georeferenced Block 53 and Block 57 layers displayed together for final spatial verification.

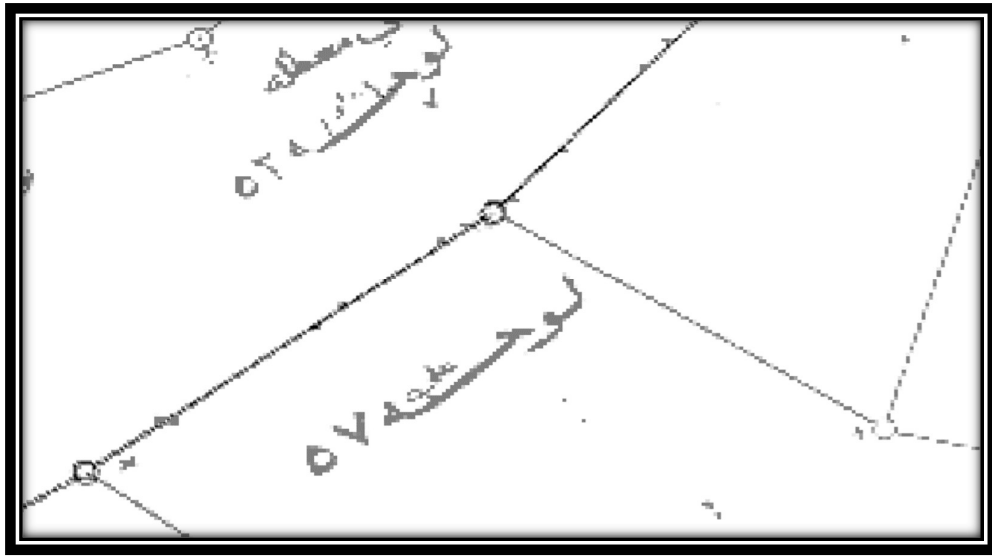


Figure 5.18. GIS verification of the common boundary between Blocks 53 and 57 after applying the boundary-conditioned adjustment and re-exporting the adjusted sheets. Source: screenshot prepared by the researcher.

Visual examination at greater magnification revealed substantially better agreement between corresponding lines and vertices after adjustment. The improvement was particularly evident at changes in direction along the common boundary, where corresponding vertices converged and boundary lines continued through the interface without an obvious break. This observation supports the conclusion that the method improved not only the individual placement of each block but also the geometric continuity between them.

Independent georeferencing can provide an acceptable fit to the GCPs within each block while still placing the same vertex at different positions on neighboring sheets. In the boundary-conditioned solution, shared-point relationships are incorporated directly into parameter estimation. Inter-block agreement is therefore addressed during the adjustment rather than corrected after each block has been transformed independently.

The adjusted results were then returned to GIS, where each adjusted coordinate was linked to a stable point or feature identifier. This procedure prevented coordinates from being

assigned to incorrect features when file-row ordering differed and preserved the traceability of every modified vertex back to its original computational record.

The GIS review provides important spatial and topological evidence; however, visual agreement alone is not a measure of numerical accuracy. It should therefore be interpreted together with RMSE values, residual statistics, and, where available, Check Point accuracy derived from an independent validation set. This combined evaluation provides a more reproducible basis for assessing positional performance.

5.13 Accuracy Assessment

5.13.1 Residuals and Root-Mean-Square Error

For an independent Check Point set of size n , coordinate differences between the surveyed reference positions and transformed positions are summarized by:

$$\text{RMSE}_x = \sqrt{[\Sigma(\Delta X_i)^2 / n]}, \quad \text{RMSE}_y = \sqrt{[\Sigma(\Delta Y_i)^2 / n]} \quad (5.10)$$

$$\text{RMSE}_r = \sqrt{(\text{RMSE}_x^2 + \text{RMSE}_y^2)} \quad (5.11)$$

RMSE_r is the combined horizontal error, whereas RMSE_x and RMSE_y reveal directional behavior. The final project stores the 166 Ground Check Points with their source and ground coordinates, so their full-network performance can be recomputed independently of parameter estimation. Using the final simultaneous transformations, the overall Ground Check Point RMSE_{2D} is 1.2015 m for Affine, 0.8001 m for Poly2, and 0.7884 m for Poly3. These values complement the internal Control Point residuals and the withheld Check Tie Point results; they are not observations used to fit the transformations.

5.13.2 Common-Boundary Continuity

Common-boundary continuity is assessed at two levels. First, residuals of Control Tie Points quantify how well the simultaneous solution satisfies the shared-boundary constraints that were included in the adjustment. Second, Check Tie Points provide an independent inter-block test because they are withheld from those constraints. For each CTP, coordinates are computed from both neighboring block transformations in the independent solution and again after the simultaneous adjustment. The differences ΔX , ΔY , and $d_{2D} = \sqrt{(\Delta X^2 + \Delta Y^2)}$ are summarized by component and two-dimensional RMSE. A reduction in CTP RMSE after the simultaneous solution is therefore stronger evidence of improved boundary continuity than a reduction in the residuals of ties that participated in the solution. Visual GIS overlays remain complementary rather than numerical evidence. Polygon-based gap and overlap areas were not available in the stored project and are therefore not reported as measured results.

5.13.3 Parcel Area and Shape

Where reference and adjusted parcel polygons are available, the relative area change can be used to identify excessive deformation of cadastral geometry:

$$\Delta A\% = |A_{\text{adjusted}} - A_{\text{reference}}| / A_{\text{reference}} \times 100 \quad (5.12)$$

The stored project does not include a vector parcel layer or paired reference and adjusted parcel-area fields, so Equation (5.12) cannot be evaluated from the supplied project alone. In the final CTP-enabled Poly3 full-network run, MapGeoref uses 540 enabled Ground Control Points and 85 Control Tie groups, while 166 Ground Check Points and 12 Check Tie groups remain excluded from parameter estimation. The combined solution RMSE is 0.7030 m and the maximum residual is 2.1682 m. The combined RMSE is calculated from 625 planar residual elements (540 Control Points + 85 Control Tie relationships) for 120 Poly3 coefficients. Parcel-area comparison therefore remains a subsequent GIS validation step.

Table 5.12. Final Poly3 full-network results by block from the audited MapGeoref configuration. RMSE elements equal enabled Control Points plus effective Control Tie occurrences associated with each block; CTP and ground Check observations are excluded.

Blk.	Active GCPs	Control Tie Occurrences Used	RMSE Elements	Final RMSE (m)	Maximum Residual (m)
51	43	12	55	0.6799	1.8108
53	108	34	142	0.7690	1.9206
54	94	43	137	0.8217	2.1682
56	135	18	153	0.6395	1.9400
57	111	41	152	0.7336	1.7044
58	49	22	71	0.6132	1.5754

Table 5.13. Internal Control Tie continuity and combined-network accuracy for the final Poly3 solution. The 85 Control Tie groups participate in estimation and are therefore internal diagnostics, not independent validation.

Indicator	Independent / Before	Simultaneous / After	Change
Mean Control Tie separation	1.3558 m	0.7876 m	41.9% decrease
Control Tie RMSE	1.5426 m	0.8682 m	43.7% decrease
Maximum Control Tie separation	3.0218 m	1.6041 m	46.9% decrease
Combined system RMSE	—	0.7030 m	Final Poly3 value
Maximum combined residual	—	2.1682 m	Final Poly3 value

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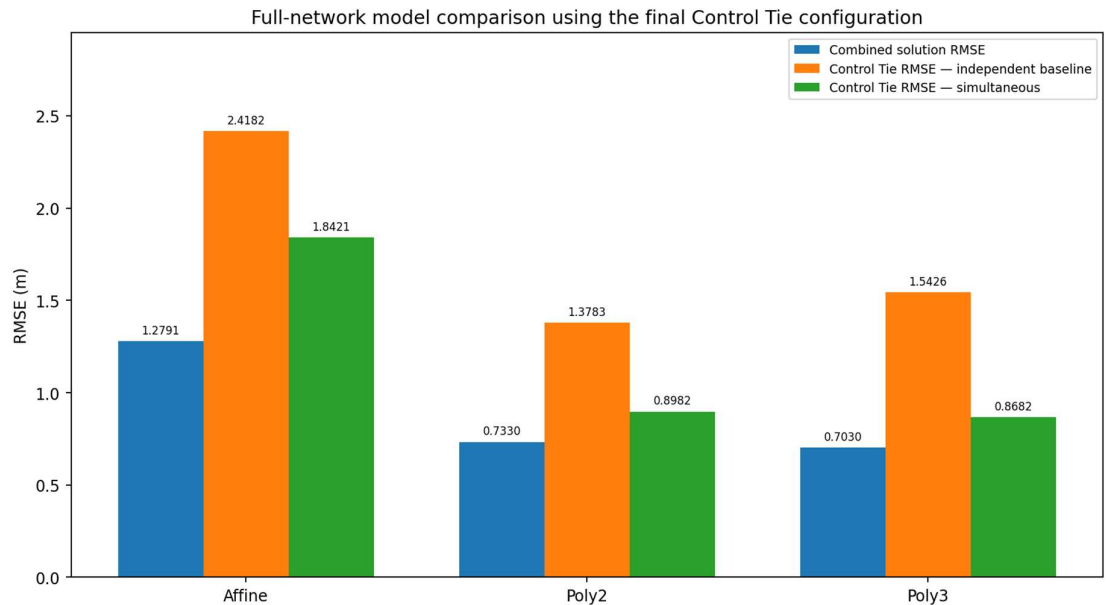


Figure 5.19. Final model comparison of combined RMSE and Control Tie RMSE before and after simultaneous adjustment using 85 Control Tie groups. Source: MapGeoref final project calculations.

5.14 Quality Control and Reliability of the Results

No single statistic was treated as sufficient evidence of an acceptable solution. The final application provides four complementary numerical checks: internal Ground Control Point residuals, internal Control Tie continuity, independent Ground Check Point accuracy, and independent Check Tie Point validation. GIS overlay inspection adds spatial evidence. In the final project, the Ground Check Point and CTP datasets are reproducible and explicitly excluded from parameter estimation; the remaining validation tasks that still require external GIS data are polygon topology, gap/overlap measurements, and parcel-area comparison.

Table 5.14. Quality-control levels and the questions addressed by each level.

Verification Level	Question Addressed
Numerical	Did the solution converge, and are residuals within acceptable limits?
Independent	Do the parameters perform adequately at points excluded from estimation?
Geometric	Do shared boundaries remain continuous without unacceptable deformation?
Spatial and visual	Do the assembled layers reveal local distortion or discontinuity?
Documentary	Can every point, decision, and correction be traced to its source?

A project copy was preserved at each major stage: after data import, after shared-point definition, after tie validation, and after the final solution. This record allows individual changes to be traced and their effects compared with earlier stages, thereby supporting reproducibility.

5.15 Practical Problems and Corrective Procedures

Table 5.15. Common implementation problems, their effects, and corrective actions.

Potential Problem	Likely Effect	Corrective Procedure
Feature unclear on the sheet	Incorrect source position	Consult a clearer copy and reject the point if doubt remains
Feature altered in the field	Coordinate does not represent the historical position	Document, exclude, or resurvey the feature
X and Y reversed	Large displacement or transformation failure	Fix column definitions and inspect coordinate ranges
Repeated local identifier	Unrelated records linked together	Use a compound identifier containing block and point numbers
Incorrect shared point	Distortion propagated to two or more blocks	Verify geometry and imagery before accepting the tie
Points clustered in one area	Weak extrapolation at the edges	Improve distribution or reduce model order
Over-flexible model	Small point residuals but distortion between points	Use independent checks and inspect geometry and area
Premature rounding	Cumulative loss of numerical precision	Retain full precision and round only for presentation

5.16 Discussion of the Implementation Workflow

The application showed that the most sensitive stage of the procedure occurs before the equations are solved: correctly identifying each point. A mathematical model cannot distinguish a correctly identified vertex from a record carrying an incorrect identifier. Enforcing coincidence between unrelated points can propagate distortion through the network; therefore, point identification and tie validation must precede the adjustment.

The implementation also demonstrated that boundary and internal observations perform different but complementary roles. Boundary points connect neighboring blocks and reduce discontinuities between them, whereas internal points help determine transformation behavior within each sheet. Strong boundary constraints can improve adjacency but may introduce internal distortion if not supported by adequate interior control. Conversely, internal control without shared relationships can improve individual blocks while leaving gaps along their edges. The proposed approach integrates both forms of evidence within a single connected system.

MapGeoref translated the mathematical approach into a transparent and repeatable workflow. The user can manage block files, identify shared points, save the project, execute the adjustment, and review the results within a single application rather than manually handling numerous tables and equations. Professional surveying judgment nevertheless remains necessary to accept field features, confirm ties, interpret unusual residuals, and select an appropriate transformation model.

5.17 Application Outputs

The developed application produces both computational and thesis-ready outputs. In addition to the saved .mapgeoref project, the one-click solution package can export 01_Result_Analysis.html, 02_Numerical_Results.csv, 03_Report_Image.png, 04_Analysis_Visualization.png, and 05_Solution_Metadata.json. The application can also export the solution matrices A , L , X , N , N^{-1} , and V as text files, as well as georeferenced raster outputs as GeoTIFF/ArcGIS-ready TIFF files in the selected coordinate reference system. These outputs make the calculations, validation results, figures, and GIS reintegration traceable to the same solved project.

Table 5.16. Principal outputs implemented in MapGeoref and their role in result verification, documentation, and GIS reintegration.

Output	Format	Purpose
Saved project	.mapgeoref	Preserve maps, points, roles, transformations, solution state, and validation reports
Result analysis	01_Result_Analysis.html	Human-readable solution summary and automatic interpretation
Numerical results	02 Numerical Results.csv	Reproducible numerical results for further analysis
Report image	03_Report_Image.png	Thesis-ready detailed report image
Analysis visualization	04 Analysis Visualization.png	Graphical RMSE / validation summary
Solution metadata	05 Solution Metadata.json	Timestamp, model, CRS, and EPSG metadata
Solution matrices	A , L , X , N , N^{-1} , V (.txt)	Audit the least-squares system and derived matrices
Georeferenced rasters	GeoTIFF / ArcGIS TIFF	Return adjusted block sheets to GIS with spatial reference
CTP validation report	HTML / Word-style report / CSV-ready results	Document independent inter-block validation before and after simultaneous adjustment

5.18 Presentation of the Application Results

This section presents the results obtained from the final audited MapGeoref project and the final Single + Tie and Full + CTP solution reports. Two states are distinguished: independent block transformations used to establish the before-adjustment baseline, and the simultaneous full-network solution in which 85 Control Tie groups connect the six blocks. The same 12 Check Tie groups remain outside the equations in both states. Model performance is therefore evaluated using internal Control Point residuals, internal Control Tie performance, independent Ground Check Points, independent CTPs, and GIS geometry.

The final results do not support selecting a transformation model from one RMSE value alone. Poly3 gives the lowest combined full-network RMSE (0.7030 m) and the lowest

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Ground Control Point RMSE_{2D} (0.6733 m), while Poly2 gives the lowest final withheld CTP RMSE_{2D} (1.0352 m, compared with 1.0788 m for Poly3). Poly3 gives the largest proportional CTP improvement (39.3%). The final overall Ground Check Point RMSE_{2D} is 0.7884 m for Poly3 and 0.8001 m for Poly2, compared with 1.2015 m for Affine. The results therefore favor a multi-criterion interpretation rather than a single-error ranking.

5.18.1 Summary of the Main Results

The improvement is demonstrated by two different forms of evidence. The 85 Control Tie groups, which are included in the solution, show a Poly3 RMSE reduction from 1.5426 m to 0.8682 m. More importantly, the 12 withheld CTP groups independently improve from 1.7771 m to 1.0788 m, while the 166 Ground Check Points give a final Poly3 RMSE_{2D} of 0.7884 m. The first measure describes how the fitted shared constraints behave; the latter two assess performance at observations not used to estimate the transformation coefficients.

Table 5.17. Summary of the principal final numerical results after auditing the application logic and final project state.

Evaluation Indicator	Before / Independent	After / Final Simultaneous	Interpretation
Poly3 Control Tie RMSE (85 groups)	1.5426 m	0.8682 m	43.7% reduction; internal constraint diagnostic
Poly3 withheld CTP RMSE _{2D} (12 groups)	1.7771 m	1.0788 m	39.3% reduction; independent inter-block validation
Poly3 Ground Check Point RMSE _{2D} (166 points)	–	0.7884 m	Independent absolute positional validation
Poly3 combined network RMSE	–	0.7030 m	540 Control Points + 85 Control Tie relationships
Poly3 maximum combined residual	–	2.1682 m	Largest final fitted residual
Final network roles	97 effective shared relationships	85 Control Ties + 12 CTPs	Only Control Ties enter the equations

5.18.2 Results by Block

Table 5.18 distinguishes stored records from the observations used in the final Poly3 solution. The column 'Control Tie occurrences used' counts the effective Control Tie occurrences attached to each block; CTP occurrences and the two singleton tie occurrences are excluded. 'RMSE elements' equals enabled Ground Control Points plus effective Control Tie occurrences for that block summary.

Table 5.18. Detailed final Poly3 adjustment results by cadastral block from the audited .mapgeoref state.

Block	Stored Records	Active GCPs	Control Tie Occurrences Used	RMSE Elements	Final RMSE (m)	Maximum Residual (m)
51	78	43	12	55	0.6799	1.8108

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Block	Stored Records	Active GCPs	Control Tie Occurrences Used	RMSE Elements	Final RMSE (m)	Maximum Residual (m)
53	177	108	34	142	0.7690	1.9206
54	172	94	43	137	0.8217	2.1682
56	189	135	18	153	0.6395	1.9400
57	191	111	41	152	0.7336	1.7044
58	95	49	22	71	0.6132	1.5754

The six block files contain 902 stored records. The final full-network solution uses 540 enabled Ground Control Points and 170 usable Control Tie occurrences representing 85 two-block Control Tie groups. A further 24 occurrences form 12 CTP groups and remain outside the equations. Two additional singleton tie occurrences (TP5 and TP45) are stored in Blocks 58 and 57 respectively but cannot create an inter-block condition because each appears in only one block.

– Corrected Dataset and Preliminary Georeferencing of Block 53

The Block 53 dataset was rechecked against the preliminary files and the final project. The preliminary independently georeferenced file contains 107 source-target coordinate pairs, whereas the final MapGeoref project stores 177 records for Block 53. The final role configuration contains 108 enabled Ground Control Points, 31 Ground Check Points, 34 effective Control Tie occurrences used in the simultaneous solution, and 4 Check Tie occurrences withheld for CTP validation. Thus, 142 elements (108 Control Points + 34 Control Tie occurrences) enter the block-level combined residual summary. In the final Poly3 network, Block 53 has a combined RMSE of 0.7690 m and a maximum residual of 1.9206 m.

Table 5.19. Technical information for Block 53 updated to the final MapGeoref project state; preliminary raster properties remain as documented in the supplied block files.

Property	Verified Value for Block 53
Number of parcels	79 parcels
Area field	1,408,013.058 m ²
Area in dunums	1,408.013058 dunums
Coordinate pairs in the preliminary independent file	107 pairs
Records in the final application project	177 records
Active GCPs	108 points
Tie-role occurrences in final project	34 Control Tie occurrences used + 4 CTP occurrences withheld
Elements in the block residual summary	142 elements
Final block RMSE	0.7690 m
Maximum final residual	1.9206 m

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Property	Verified Value for Block 53
Original sheet dimensions	10,720 × 8,359 pixels
Scan resolution	300 dpi
Embedded preliminary transformation	Second-order polynomial
Final application model	Third-order polynomial (Poly3)
Coordinate reference system	Palestine Grid 1923 Modified TM
Spatial identifier	ESRI 103699
Coordinate unit	meter
First output raster	2,764 × 2,520 pixels; 1 m cell size
Second output raster	2,506 × 2,544 pixels; 1 m cell size

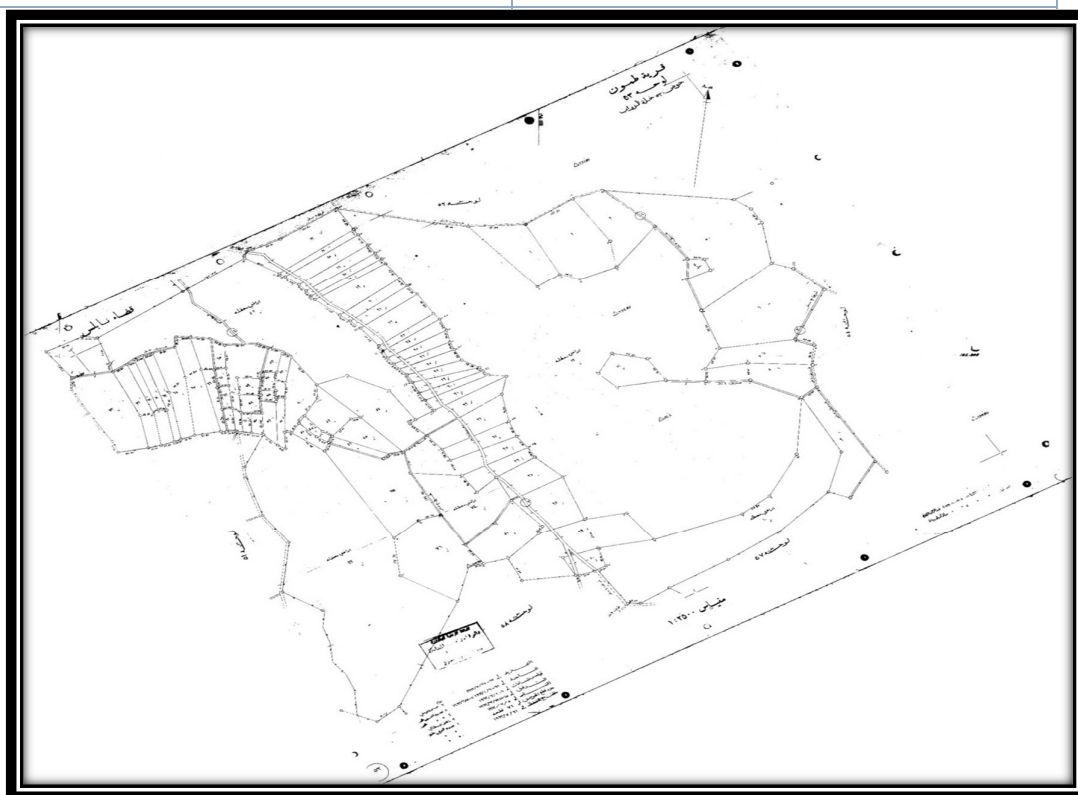


Figure 5.20. Block 53 sheet after preliminary georeferencing, shown in the supplied raster output. Source: practical study data.

Visual inspection confirmed that the entire sheet frame, block boundary, and internal parcel geometry were visible in the georeferenced raster. Resampling created transparent areas outside the rotated sheet that do not belong to the cadastral block. Any subsequent area or other spatial analyses should therefore be clipped to the sheet extent or a block mask.

5.18.3 Comparison Before and After Simultaneous Adjustment

The independent (pre-adjustment) case is obtained by solving each block independently from its enabled Ground Control Points and then evaluating the shared-point separations. In the final simultaneous case, all six blocks are solved together with 85 Control Tie groups in the equations. The same 12 CTP groups are deliberately withheld and recalculated only

for validation. The complete effective shared-point pool therefore contains 97 relationships (85 Control + 12 Check), but only the 85 Control Tie relationships participate in parameter estimation.

The project file did not save a static image of each block before adjustment. Therefore, no reconstructed screenshot is presented as though it were a saved application view. Instead, the before-and-after comparison is based on values that can be recomputed from the stored records. Future runs should save both views at the same map scale and extent to allow direct visual comparison.

5.18.4 Protocol for Comparing the Three Transformation Models

The Affine, second-order polynomial, and third-order polynomial models were compared using the same final role configuration: 540 enabled Ground Control Points, 85 Control Tie groups used as inter-block constraints, 166 Ground Check Points excluded from estimation, and 12 Check Tie groups reserved for independent inter-block validation. No differential weights or distance constraints were used. This common configuration permitted direct comparison of model behavior without changing the validation sample.

Table 5.20. Component residual statistics for the 540 enabled Ground Control Points in the final full-network configuration.

Model	GCP Count	E Min (m)	E Max (m)	E RMSE (m)	N Min (m)	N Max (m)	N RMSE (m)
2D Affine	540	-2.462	3.141	0.805	-3.626	3.264	0.844
2nd Order	540	-2.092	1.468	0.515	-1.425	1.902	0.479
3rd Order	540	-1.952	1.449	0.490	-1.495	1.840	0.462

Table 5.21. Horizontal Ground Control Point residual statistics for the final simultaneous full-network solutions.

Model	Minimum Horizontal Residual (m)	Maximum Horizontal Residual (m)	Mean Horizontal Residual (m)	Horizontal RMSE (m)
2D Affine	0.021	3.959	0.931	1.166
2nd Order	0.024	2.195	0.606	0.704
3rd Order	0.023	2.168	0.573	0.673

The horizontal Ground Control Point RMSE decreases from 1.166 m for Affine to 0.704 m for Poly2 and 0.673 m for Poly3. The maximum Ground Control Point residual decreases from 3.959 m to 2.195 m and 2.168 m, respectively. These values describe the internal fit to the 540 enabled Control Points; they are interpreted together with the independent Ground Check Point and CTP results rather than as stand-alone evidence of model quality.

Table 5.22. Internal Control Tie residual statistics before and after simultaneous adjustment for the 85 Control Tie groups used in the final equations.

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Model	Control Tie Count	RMSE Before (m)	RMSE After (m)	Mean Before (m)	Mean After (m)	RMSE Improvement (%)
2D Affine	85	2.4182	1.8421	2.2090	1.6192	23.8
2nd Order	85	1.3783	0.8982	1.2499	0.8200	34.8
3rd Order	85	1.5426	0.8682	1.3558	0.7876	43.7

For the fitted Control Tie constraints, Poly3 produces the largest proportional RMSE reduction, 43.7%, and the smallest post-adjustment Control Tie RMSE, 0.8682 m, compared with 0.8982 m for Poly2 and 1.8421 m for Affine. Because these 85 ties participate in estimation, this is an internal continuity diagnostic. Independent inter-block validation is provided separately by the 12 withheld CTP groups in Table 5.26.

5.19 Ground Control and Independent Check Point Results

5.19.1 Ground-Control-Point Residuals

GCP residuals indicate the quality of the fitted model and the field coordinates used in parameter estimation. Observations with undue influence were identified by examining their easting, northing, and total horizontal components. Small GCP residuals are necessary but not sufficient because a flexible transformation can fit the control observations while producing distortion between them.

Table 5.23. Ground Control Point residual statistics by block for the final Poly3 full-network solution using 540 enabled Control Points.

Blk.	GCP Count	E RMSE (m)	N RMSE (m)	Horizontal RMSE (m)	Maximum GCP Residual (m)
51	43	0.380	0.518	0.642	1.811
53	108	0.541	0.483	0.725	1.921
54	94	0.562	0.535	0.776	2.168
56	135	0.435	0.402	0.592	1.940
57	111	0.523	0.421	0.671	1.704
58	49	0.355	0.454	0.576	1.300

5.19.2 Independent Check Point Results and Validation Status

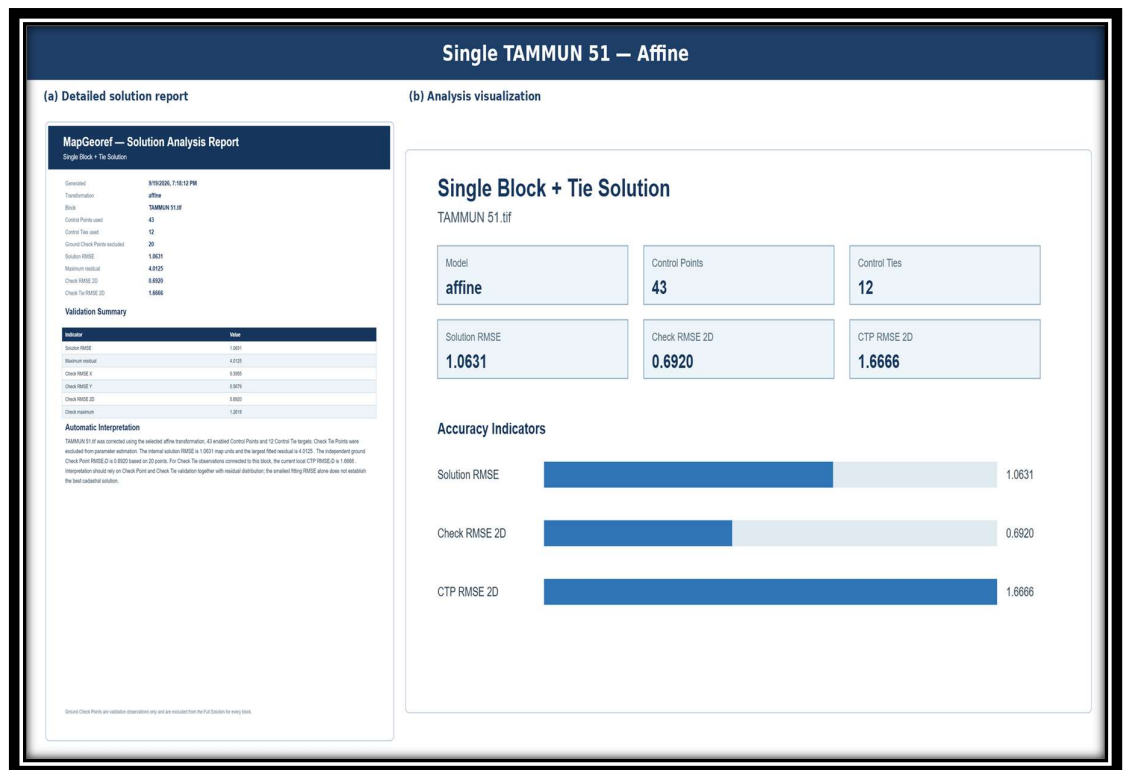
The final project contains 166 Ground Check Points, and MapGeoref excludes all of them from parameter estimation in every tested full-network model. Recalculation from the final simultaneous transformations gives overall Ground Check Point RMSE_{2D} values of 1.2015 m for Affine, 0.8001 m for Poly2, and 0.7884 m for Poly3. In the separate Single block + Tie validation for Block 51, 20 Ground Check Points are also withheld; their RMSE_{2D} values are 0.6920 m, 0.6524 m, and 0.6269 m for Affine, Poly2, and Poly3, respectively. The full-network and single-block check results therefore provide independent absolute-position tests, while the CTP results provide independent relative inter-block tests.

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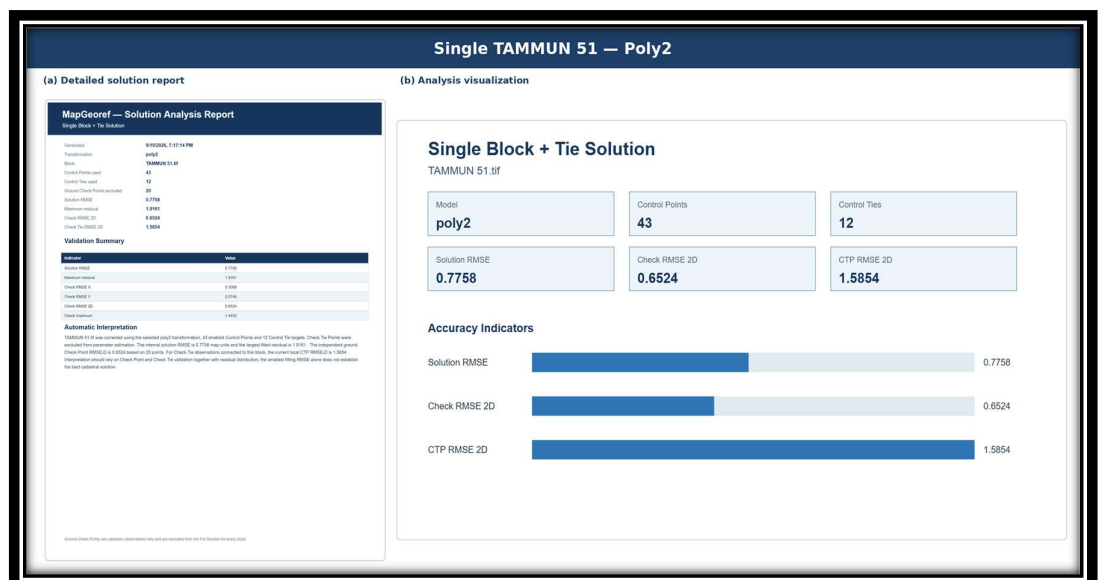
Table 5.24. Independent Ground Check Point and local Check Tie Point validation for Block 51 in the final MapGeoref single-block runs.

Model	Solution RMSE (m)	Ground Check RMSE _{2D} (m), n = 20	Local CTP RMSE _{2D} (m)
2D Affine	1.0631	0.6920	1.6666
2nd Order	0.7758	0.6524	1.5854
3rd Order	0.7028	0.6269	1.7689

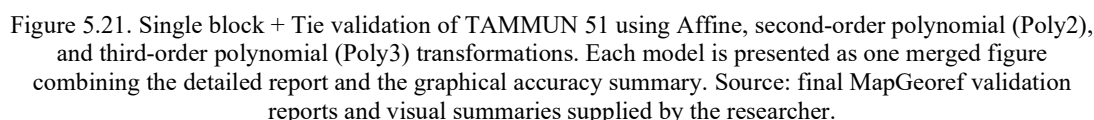
Single block + Tie — TAMMUN 51 — Affine



Single block + Tie — TAMMUN 51 — Second-order polynomial (Poly2)



Single block + Tie — TAMMUN 51 — Third-order polynomial (Poly3)



Analysis of Figure 5.21. The Block 51 results show a clear reduction in the internal solution RMSE from 1.0631 m for Affine to 0.7758 m for Poly2 and 0.7028 m for Poly3. Independent Ground Check Point RMSE_{2D} also decreases progressively from 0.6920 m to 0.6524 m and then to 0.6269 m, while the maximum fitted residual falls from 4.0125 m to 1.9161 m and 1.8576 m. The local Check Tie Point behavior is different: Poly2 gives the lowest local CTP RMSE_{2D} (1.5854 m), compared with 1.6666 m for Affine and 1.7689 m for Poly3. This distinction is important because it shows that the model with the smallest internal or Ground Check Point error does not necessarily provide the smallest local inter-block discrepancy. The Block 51 comparison therefore supports evaluating model performance with independent Ground Check Points and Check Tie Points together rather than relying on solution RMSE alone.

Table 5.25. Final availability and methodological role of the verification datasets in the audited MapGeoref project.

Verification Dataset	Final Audited Status	Implication
Ground Control / Ground Check Points	540 enabled Control Points enter estimation; 166 Ground Check Points are excluded and retained for validation.	Internal fit and independent absolute-position validation are kept separate.
Effective shared relationships	97 effective two-block relationships = 85 Control Tie groups + 12 Check Tie groups.	The shared-point pool is explicitly split into constraints and independent validation.

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Verification Dataset	Final Audited Status	Implication
Singleton tie identifiers	2 stored singleton identifiers: TP5 and TP45.	They form no inter-block equation and are not counted among the 97 effective relationships.
Check Tie Points (CTPs)	12 CTP groups are excluded for all three model comparisons and reported before/after.	Provides reproducible independent inter-block validation.
Single-block ground checks for Block 51	20 independent Ground Check Points are reported for Affine, Poly2, and Poly3.	Provides reproducible block-level external positional validation.

5.20 Tie-Point Results and Inter-Block Continuity

5.20.1 Tie-Point Differences Before and After Adjustment

Tie points provide a direct pointwise measure of separation between adjoining blocks. Under independent transformations, a shared cadastral vertex yielded a different transformed coordinate in each block. When the tie conditions were introduced into the simultaneous system, corrections were distributed among the parameters of connected blocks, reducing the easting and northing differences and the resulting planar separation. The tie-point statistics already reported in this chapter are based on shared relationships used in the connected adjustment and must therefore be interpreted as internal constraint-performance indicators. They demonstrate improved agreement of the constrained shared points but are not, by themselves, an independent validation set.

Independent inter-block validation was completed using 12 Check Tie Point (CTP) groups that were deliberately withheld from the boundary-condition equations. For the affine model, the CTP RMSE_{2D} decreased from 2.2823 m in the independent baseline to 1.7250 m after simultaneous adjustment, an improvement of 24.4%. For the second-order polynomial, it decreased from 1.4695 m to 1.0352 m, an improvement of 29.6%. For the third-order polynomial, it decreased from 1.7771 m to 1.0788 m, representing the largest proportional improvement, 39.3%. Because the same withheld CTPs remained outside parameter estimation, these reductions constitute independent evidence that the simultaneous adjustment improved relative agreement between neighboring blocks beyond the points used to enforce continuity.

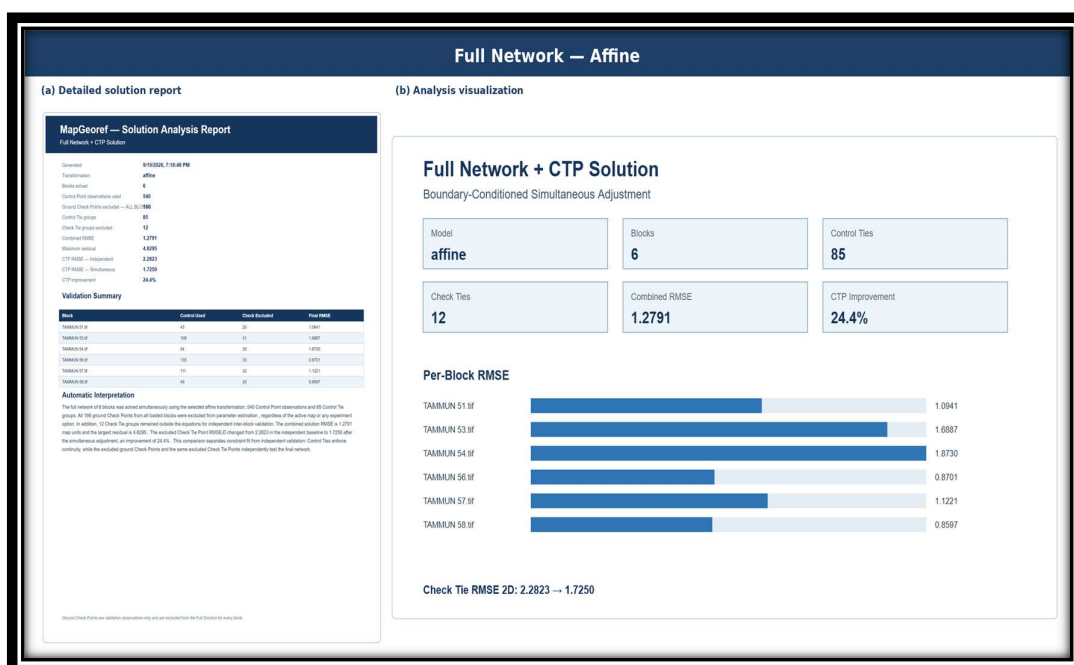
The CTP comparison also reveals an important model-selection distinction. Poly3 produced the largest percentage reduction in CTP RMSE_{2D}, but Poly2 produced the lowest final CTP RMSE_{2D} (1.0352 m), which is 0.0436 m lower than the Poly3 result. Consequently, percentage improvement and final absolute discrepancy should both be reported. The final CTP-enabled run used 540 Control Point observations and 85 Control Tie groups in the equations; the 12 CTP groups remained excluded throughout the before-and-after comparison.

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Table 5.26. Full-network Check Tie Point validation from the final MapGeoref reports. The same 12 CTP groups were withheld from parameter estimation for all three models.

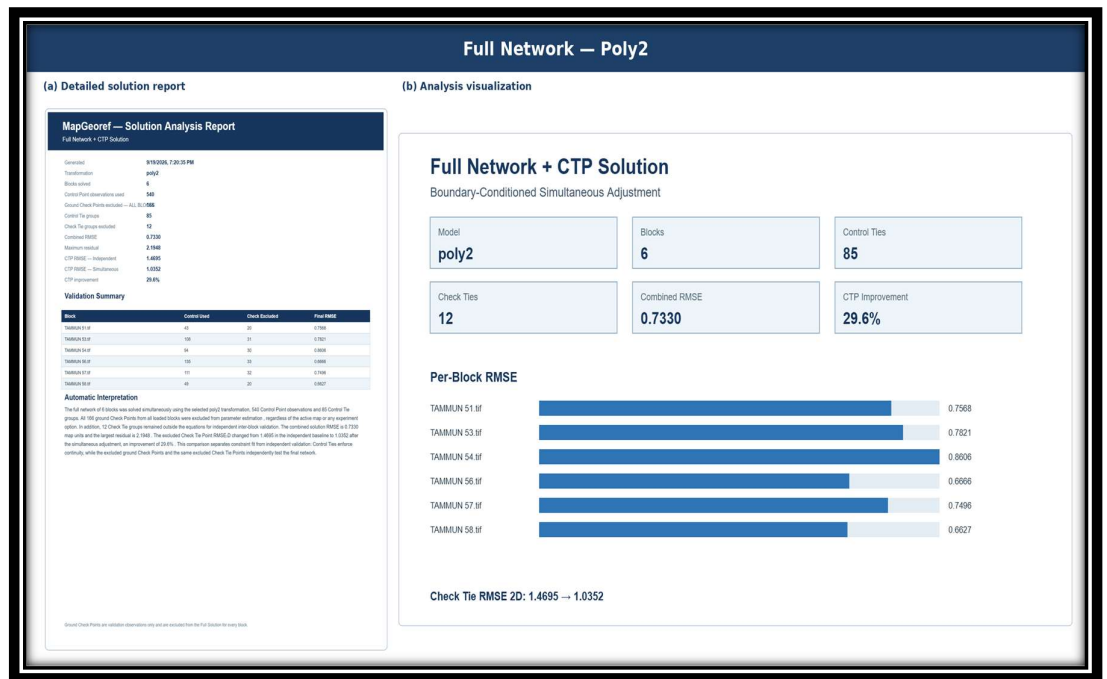
Model	Combined RMSE (m)	Maximum Residual (m)	CTP RMSE _{2D} Before (m)	CTP RMSE _{2D} After (m)	Gain (%)
2D Affine	1.2791	4.8295	2.2823	1.7250	24.4
2nd Order	0.7330	2.1948	1.4695	1.0352	29.6
3rd Order	0.7030	2.1682	1.7771	1.0788	39.3

Full Network + CTP — Affine



Full Network + CTP — Second-order polynomial (Poly2)

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Full Network + CTP — Third-order polynomial (Poly3)

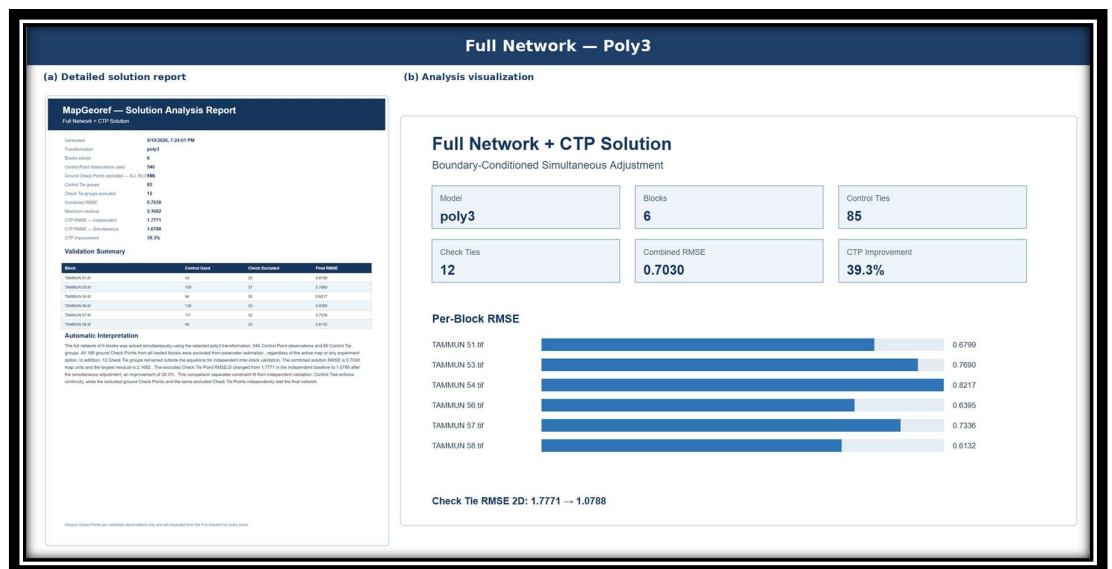


Figure 5.22. Full Network + CTP validation for the six-block simultaneous adjustment using Affine, second-order polynomial (Poly2), and third-order polynomial (Poly3) transformations. Each model is presented as one merged figure combining the detailed MapGeoref report and the graphical six-block RMSE and CTP validation summary. Source: final MapGeoref validation reports and visual summaries supplied by the researcher.

Analysis of Figure 5.22. The full-network results confirm that increasing transformation flexibility substantially improves the overall fitted network. Combined RMSE decreases from 1.2791 m for Affine to 0.7330 m for Poly2 and 0.7030 m for Poly3, while the maximum residual decreases from 4.8295 m to 2.1948 m and 2.1682 m. Independent inter-block validation using the same 12 withheld Check Tie Point groups also improves after

simultaneous adjustment in all three models: from 2.2823 to 1.7250 m for Affine (24.4%), from 1.4695 to 1.0352 m for Poly2 (29.6%), and from 1.7771 to 1.0788 m for Poly3 (39.3%). Poly3 gives the lowest combined RMSE and the largest proportional CTP improvement, whereas Poly2 gives the smallest final CTP RMSE_{2D} by 0.0436 m. Accordingly, Figure 5.22 supports the same methodological conclusion as the numerical tables: model selection should consider absolute positional fit, independent inter-block validation, and shared-boundary behavior together rather than choosing a model from a single RMSE value.

Table 5.27. Distribution of the final 85 Control Tie groups and 12 withheld Check Tie groups across common block boundaries.

Common Boundary	Control Ties	CTPs	Total Relationships
51–53	8	3	11
51–58	4	0	4
53–54	11	1	12
53–57	6	0	6
53–58	9	0	9
54–56	12	2	14
54–57	20	2	22
56–57	6	1	7
57–58	9	3	12
Total	85	12	97

The smaller tie-point residuals mean that the two representations of a common point moved closer to each other, but the result must be interpreted in conjunction with the GCP residuals and independent Check Point residuals. Perfect inter-block coincidence with very poor agreement with field control may indicate an incorrect tie or excessive model flexibility. The resulting adjustment provides a feasible solution that improves connectivity while maintaining acceptable external positioning.

5.20.2 Connectivity of the Block Network

The blocks are not equally connected. A block with well-distributed ground control and reliable ties can stabilize its neighbors through the connected normal system. In the final role configuration, the 97 effective relationships are distributed as 85 Control Tie constraints and 12 withheld CTPs. A block connected through only a short boundary segment remains more sensitive to relative rotation or local distortion away from the connection.

The strongest numerical interface is between Blocks 54 and 57 with 22 total relationships, of which 20 are Control Ties and 2 are CTPs. The 54–56 interface contains 14 relationships (12 Control, 2 CTP), whereas the 51–58 interface contains only four, all of them Control

Ties. Block 53 is connected to four adjacent blocks through 38 effective relationships in total, partitioned into 34 Control Ties and 4 CTPs, so it acts as a central node in the shared-point network.

Figure 5.19 shows the tie-point RMSE before and after simultaneous adjustment for all three transformation models.

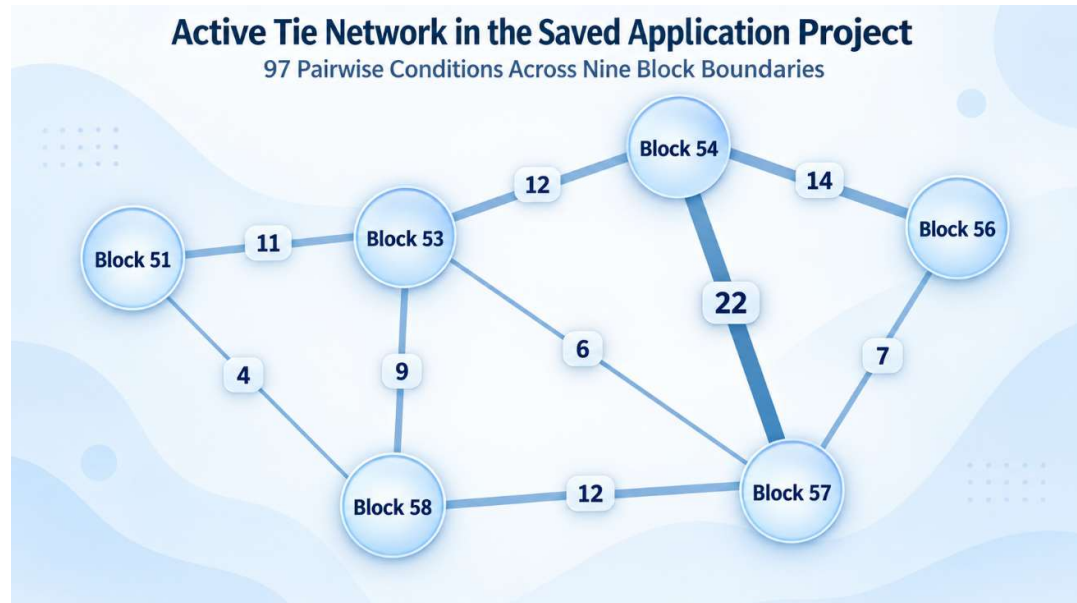


Figure 5.23. Block-connectivity network based on the number of effective tie relationships in the final project. Source: prepared by the researcher from MapGeoref project data.

5.21 Pointwise Boundary-Separation Results

For the 85 Control Tie relationships used in the final reported adjustment, the Poly3 mean pointwise separation decreases from 1.3558 m to 0.7876 m, the Control Tie RMSE decreases from 1.5426 m to 0.8682 m, and the maximum separation decreases from 3.0218 m to 1.6041 m. These quantities are internal continuity diagnostics because the Control Ties participate in estimation. Independent evidence is supplied by the 12 withheld CTP groups, whose Poly3 RMSE_{2D} improves from 1.7771 m to 1.0788 m (39.3%).

Table 5.28. Pointwise continuity statistics for the 85 Control Tie groups in the final Poly3 configuration.

Poly3 Control-Tie Continuity Indicator	Before (m)	After (m)	Improvement (%)
Mean Control Tie separation	1.3558	0.7876	41.9
Control Tie RMSE	1.5426	0.8682	43.7
Maximum Control Tie separation	3.0218	1.6041	46.9

The stored project did not contain final boundary polygons or a topology report from which gap and overlap areas could be calculated. No areal values of this type are therefore attributed to the project. Completing this test requires exporting the adjusted polygon boundaries to GIS and running gap and overlap topology checks.

5.22 Status of the Parcel-Area Comparison

MapGeoref did not store a vector parcel layer or paired reference and adjusted area fields. A valid numerical comparison of parcel areas before and after adjustment could therefore not be reproduced from the project. The stored output was limited to block images, GCPs, tie points, transformation parameters, and residuals. Parcel-area analysis must consequently be completed after export to GIS; estimated values should not be presented in place of measured results.

Table 5.29. Data requirements and current status of the parcel-area comparison.

Data Required for Area Comparison	Availability in the Project	Required Action
Parcel identifiers	Not available	Add or join the parcel layer
Reference parcel areas	Not available	Obtain from the approved record
Post-transformation areas	Not available	Calculate in GIS from adjusted polygons
Percentage change	Not currently computable	Calculate after the preceding values are available

5.23 Comparison of Transformation Models

Three transformation models were compared: a 2D affine transformation, a second-order polynomial, and a third-order polynomial. The affine transformation has six parameters representing translation, rotation, differential scale, and shear, with readily interpretable geometric behavior. The polynomial models provide increasing flexibility for representing the irregular distortion of historical sheets. However, higher-order models require a larger number of well-distributed points and carry a greater risk of overfitting.

Table 5.30. Final comparison of the three transformation models using the audited project state and both internal and independent validation indicators.

Model	GCP RMSE _{2D} (m)	Ground Check RMSE _{2D} (m)	Control Tie RMSE After (m)	Combined RMSE (m)	CTP RMSE After (m)	CTP Gain (%)
2D Affine	1.1660	1.2015	1.8421	1.2791	1.7250	24.4
2nd Order	0.7035	0.8001	0.8982	0.7330	1.0352	29.6
3rd Order	0.6733	0.7884	0.8682	0.7030	1.0788	39.3

The final comparison shows why model selection should not be based on a single statistic. Poly3 has the lowest Ground Control Point RMSE_{2D} (0.6733 m), the lowest combined RMSE (0.7030 m), the lowest Control Tie RMSE after adjustment (0.8682 m), and the largest proportional CTP improvement (39.3%). Poly2, however, has the lowest final withheld CTP RMSE_{2D} (1.0352 m versus 1.0788 m for Poly3). The independent full-

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network Ground Check Point RMSE_{2D} is 0.8001 m for Poly2 and 0.7884 m for Poly3. Thus, the two polynomial models are close in absolute validation performance, while Poly3 provides slightly lower internal and Ground Check Point errors and Poly2 provides the smallest final withheld CTP discrepancy.

5.24 Factors Affecting the Results

5.24.1 Number and Distribution of Points

The results confirmed that spatial distribution is more important than simply increasing the number of points. Where GCPs were distributed around a block and supplemented by internal observations, parameter estimation was more stable and edge behavior depended less on extrapolation. Conversely, local clustering of points left some areas more susceptible to distortion even when the total number of points in the block was sufficient.

5.24.2 Type and Condition of the Field Feature

Positions derived from cadastral crosses, iron corner monuments, and stable stone features produced more consistent results than positions derived from thick drawn lines or features altered over time. Their principal advantage is that the same physical center can be identified more precisely on both the sheet and the ground. Differences in feature quality were also reflected in residual magnitude and in decisions to accept or reject individual observations, reinforcing the need to verify each feature before adjustment.

5.24.3 Correct Identification of Shared-Boundary Points

The effectiveness of the boundary conditions depends directly on correct tie-point identification. A valid tie transfers consistency to adjacent blocks and reduces separation along their interface. Conversely, an incorrect match can propagate distortion through the network without necessarily being evident in a single summary statistic. Each tie was therefore checked descriptively, spatially, and visually, and a candidate was rejected when the two occurrences did not represent the same vertex or feature. The same review standard applies to CTP selection: a CTP must be a confidently identified shared feature, but its role is changed from a constraint to an independent validation observation before the solution is formed.

5.24.4 Historical Sheet Distortion

Distortion varied within and between the sheets because of historical survey and drafting methods, line weight, the 1:2,500 map scale, paper deformation, scanning, and digitization. A drafting uncertainty of 0.2–0.3 mm corresponds to about 0.50–0.75 m on the ground at this scale and accounts for a large part of the initial differences. Therefore, it was not

realistic to expect full agreement from a simple transformation applied uniformly to all sheets.

5.24.5 Role of Independent Check Points and Check Tie Points in Controlling Overfitting

Independent Ground Check Points and Check Tie Points address two different forms of overfitting. Ground Check Points test whether a transformation that fits its GCPs predicts independent field positions, while CTPs test whether a connected solution that fits its Control Tie constraints also improves shared locations that were not used as constraints. A higher-order model can reduce GCP or Control Tie residuals without improving either independent validation set. Model selection should therefore consider Check Point RMSE and CTP RMSE together with GCP residuals, Control Tie residuals, spatial residual patterns, and GIS geometry. The updated MapGeoref application maintains these validation roles separately and can export their results independently.

5.25 Independent Georeferencing versus Simultaneous Adjustment

Independent georeferencing treats each sheet as a separate unit, so the objective function considers only agreement with the GCPs assigned to that block. No information within the solution directly forces a vertex to coincide with its counterpart on a neighboring sheet. Consequently, each block may achieve an acceptable RMSE independently while gaps or offsets remain when the blocks are assembled.

The simultaneous approach adds the shared relationships to the same adjustment system. Consequently, an improvement in one block is constrained by its effect on connected neighbors, and corrections are distributed across the network rather than confined to a single block edge. This produces a more consistent cadastral fabric. The principal contribution of the study is this shift from correcting isolated sheets to adjusting a connected cadastral network.

The CTP procedure tests whether this network-level improvement generalizes beyond the shared points that were used to force continuity. Under the independent solution, a CTP receives one transformed coordinate from each neighboring block; after the simultaneous solution, it is recalculated from both adjusted transformations while remaining outside the constraint system. A smaller post-adjustment CTP discrepancy therefore provides an independent measure of improved relative block geometry.

Comparison Between Independent Georeferencing and Simultaneous Adjustment

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Aspect	Independent georeferencing	Simultaneous adjustment
Processing unit	One block	All connected blocks
Shared points	Not imposed as direct conditions	Control Ties are included as constraints; CTPs remain excluded for validation
Common boundaries	May retain gaps and offsets	Subject to continuity conditions
Distribution of corrections	Within one block only	Across the network through boundary conditions
Evaluation	Usually block-level RMSE	Control RMSE, ground checks, Control Ties, withheld CTPs, GIS topology, and area when available
Cadastral suitability	Limited when sheets are assembled	Greater consistency for the connected fabric

5.26 Discussion in Relation to Previous Studies

The results support treating the cadastral sheets as a connected spatial fabric rather than as isolated graphic objects. Historical sheet distortion is spatially irregular, and independent transformations can leave mismatches along common boundaries even where each block has an acceptable internal RMSE. In the implemented MapGeoref workflow, this connected geometry is introduced directly through Control Tie equations in one least-squares design matrix; the Affine, Poly2, and Poly3 coefficient systems used for the reported experiments are solved linearly from the assembled normal equations.

The audited final project state contains 540 enabled Ground Control Points and 166 independent Ground Check Points. Its 99 shared-point identifiers consist of 85 effective Control Tie groups used in estimation, 12 effective Check Tie groups withheld for validation, and two singletons that form no inter-block relation. Reporting these roles separately is essential for reproducibility because the Control Ties describe fitted continuity, whereas the ground checks and CTPs test performance at observations that did not contribute to parameter estimation.

This interpretation is consistent with the principles of land administration and georeferencing described by Enemark et al. (2014), Longley et al. (2015), San-Antonio-Gómez et al. (2015), Forejt et al. (2020), Younis (2020), and Younis et al. (2025).

5.27 Practical Implications and Limitations

5.27.1 Practical Implications

The observed improvement indicates that the method is useful for modernizing historical cadastral block sheets for GIS applications, particularly when independently georeferenced adjacent sheets conflict along common boundaries. In addition, MapGeoref maintains a reviewable record of points, ties, and residuals, enabling the surveyor to revisit decisions or rerun the solution when new field observations become available.

The results can support the creation of cadastral databases, help identify potentially conflicting interfaces before settlement work begins, and focus further surveys on blocks or boundaries with weak control. An improved geometric solution does not replace legal procedures or field adjudication of ownership rights; rather, it provides a more coherent technical basis to support them.

5.27.2 Study Limitations

Accuracy remains dependent on the quality of the source sheets, the discernibility of surviving features, the number and spatial distribution of observations, the validity of tie-point identification, and the appropriateness of the transformation model. Some distortion inherent in historical surveys cannot be fully separated from later physical changes on the ground. The final CTP export resolves the previous limitation concerning independent inter-block validation, but the CTP sample is still limited to 12 withheld groups and remains a point-based test. It does not replace polygon-based topology checks, gap/overlap measurements, parcel-area comparisons, or validation in additional study areas. Numerical results should therefore be interpreted as evidence for the tested Tammun network rather than as universal fixed accuracy thresholds.

A further caveat is that a lower RMSE does not, by itself, indicate the legal or cadastral implications of a coordinate correction. For this reason, original and adjusted coordinates should always be preserved together, reasons for rejecting points or ties should be documented, and sensitive cases should be reviewed by experienced professionals before official acceptance.

5.28 Summary

This chapter described the implemented MapGeoref workflow from field evidence to final validation. After preliminary GIS georeferencing, point roles and shared relationships were reviewed in the application. For the Affine, Poly2, and Poly3 experiments, MapGeoref assembled a connected linear least-squares system, solved the transformation coefficients directly through the normal equations, calculated internal Control Point and Control Tie

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residuals, and then evaluated the independent Ground Check Point and Check Tie Point datasets. The results and transformation outputs were exported for numerical review, report generation, and GIS reintegration.

The audited final run uses 540 enabled Ground Control Points and 85 Control Tie groups in the equations, while 166 Ground Check Points and 12 Check Tie groups remain excluded from parameter estimation. Poly3 produces a combined network RMSE of 0.7030 m, a Ground Control Point RMSE_{2D} of 0.6733 m, a full-network Ground Check Point RMSE_{2D} of 0.7884 m, and a Control Tie RMSE reduction from 1.5426 m to 0.8682 m (43.7%). The withheld Poly3 CTP RMSE_{2D} decreases from 1.7771 m to 1.0788 m (39.3%), while Poly2 gives the lowest final CTP RMSE_{2D} of 1.0352 m. Poly3 per-block combined RMSE values range from 0.6132 m in Block 58 to 0.8217 m in Block 54. These results show improved inter-block consistency while confirming that the smallest internal error and the smallest withheld CTP discrepancy need not occur in the same transformation model. Polygon-based topology and parcel-area checks remain necessary for complete cadastral validation.

Chapter 6

Conclusions and Recommendations

6.1 Introduction

This study addressed the georeferencing of historical Jordanian cadastral settlement block sheets in Palestine, focusing on inconsistencies that arise along common boundaries when neighboring sheets are transformed independently. To address this issue, a boundary-conditioned least-squares method was developed in which neighboring blocks are treated as components of a single connected cadastral fabric rather than as isolated maps. The methodology was applied to six connected blocks in Tammun (51, 53, 54, 56, 57, and 58), comprising 902 stored point records and 430 parcels with a total area of approximately 7,282.5 dunums. The validation framework distinguishes absolute accuracy at independent Ground Check Points from relative inter-block accuracy at withheld Check Tie Points.

6.2 Conclusions

The results confirmed that the main challenge in historical cadastral georeferencing is not only positional error within each individual block but also geometric agreement among adjacent blocks. A block can produce an acceptable RMSE independently while offsets remain at shared vertices and boundaries. Cadastral accuracy must therefore be assessed in two complementary dimensions: absolute agreement with independent Ground Check Points and relative continuity at shared locations withheld as Check Tie Points. The final MapGeoref reports demonstrate that both forms of validation can be kept outside parameter estimation, providing a stronger basis for judging whether the connected adjustment generalizes beyond the observations used to fit it.

The simultaneous adjustment produced a measurable improvement in inter-block consistency for the shared relationships used in the connected solution. For the third-order polynomial solution, the mean Control Tie separation decreased from 1.3558 m to 0.7876 m, a reduction of 41.9%. The Control Tie RMSE was reduced from 1.5426 m to 0.8682 m, an improvement of 43.7%, and the maximum Control Tie separation was reduced from 3.0218 m to 1.6041 m, a 46.9% reduction. These values demonstrate improved fit of the shared constraints and support the practical value of introducing common-boundary conditions (Table 5.28; Figure 5.19). They should, however, be described as internal Control Tie consistency indicators rather than as independent CTP accuracy.

The independent Check Tie Point results provide direct quantitative validation of the connected solution. Twelve CTP groups were withheld from all boundary-condition

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equations. Their RMSE_{2D} decreased from 2.2823 m to 1.7250 m for the affine model (24.4%), from 1.4695 m to 1.0352 m for the second-order polynomial (29.6%), and from 1.7771 m to 1.0788 m for the third-order polynomial (39.3%). Therefore, the simultaneous adjustment improved relative agreement at shared locations that did not participate in the solution. Poly3 produced the greatest proportional improvement, while Poly2 produced the lowest absolute post-adjustment CTP RMSE_{2D} (Table 5.26; Figure 5.22).

In the final CTP-enabled network run, the combined solution RMSE decreased from 1.2791 m for the affine transformation to 0.7330 m for the second-order polynomial and 0.7030 m for the third-order polynomial. The third-order model therefore retained the best internal network fit and the greatest proportional CTP improvement. Nevertheless, the second-order model achieved a slightly lower final CTP RMSE_{2D} (1.0352 m) than Poly3 (1.0788 m), a difference of 0.0436 m. This finding is important for model selection: higher model order should not be accepted solely because it reduces the fitting RMSE. Independent Ground Check Points, withheld CTPs, residual patterns, and GIS inspection must be evaluated together to control overfitting and preserve cadastral geometry (Tables 5.26 and 5.30; Figure 5.22).

A further conclusion from the audited project structure is that reproducible validation depends on a clear separation between observations used for estimation and observations reserved for testing. In the final project, 540 Ground Control Points and 85 Control Tie groups entered the connected solution, while 166 Ground Check Points and 12 Check Tie groups remained outside parameter estimation. This separation makes it possible to report internal fit and independent validation without conflating the two (Tables 5.11, 5.25, and 5.26).

Accuracy was not uniform across the six blocks. In the final Poly3 CTP-enabled run, the per-block combined RMSE values were 0.6799 m for Block 51, 0.7690 m for Block 53, 0.8217 m for Block 54, 0.6395 m for Block 56, 0.7336 m for Block 57, and 0.6132 m for Block 58. Block 58 recorded the lowest value and Block 54 the highest in this run. The variation is consistent with nonuniform historical-sheet distortion and with differences in sheet condition, observation distribution, field evidence, and network connectivity; it should not be attributed to any single cause without additional controlled testing (Table 5.12; Figure 5.16).

The study also showed that the spatial distribution and reliability of control and tie points are more important than their number alone. Well-distributed control points provide more stable transformations, whereas clustered points may give strong local agreement but

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weaker behavior near sheet edges. Likewise, tie points should represent the same cadastral vertex in both adjoining blocks and should be distributed along the common boundary. Cadastral crosses, iron corner monuments, and permanent stone features provided the most defensible field evidence when they were clearly preserved, whereas ambiguous or altered features required rejection or cautious use (Table 5.27; Figures 5.15 and 5.23).

Some discrepancies are consistent with the historical production characteristics of the sheets. At a scale of 1:2,500, a drafting error of 0.2–0.3 mm corresponds to approximately 0.50–0.75 m on the ground, even before the additional effects of paper deformation, copying, scanning, and digitization are considered. Accordingly, centimeter-level agreement should not be expected from historical paper sheets solely because modern field observations are highly precise (Equation 3.16; Figure 3.8).

The mathematical framework was implemented in the MapGeoref application, providing a repeatable workflow for connected adjustment, residual review, project saving, and GIS export. The main contribution is the transition from independent sheet correction to a connected cadastral-network solution. The available results demonstrate improved pointwise boundary continuity (Table 5.28; Figure 5.18). Polygon-based gap/overlap areas and parcel-area preservation were not numerically validated because the final project did not contain the required polygon and paired area datasets (Table 5.29); these analyses therefore remain tasks for subsequent GIS validation. The application also supports Control Tie/Check Tie role assignment, CTP before/after comparison, and dedicated CSV, HTML, and academic-report outputs (Table 5.16; Figures 5.14a, 5.14b, and 5.15).

6.3 Recommendations

Based on the results of the present study and the limitations encountered in the practical application, the following recommendations are proposed to improve the rehabilitation and modern use of historical Jordanian cadastral settlement block sheets in Palestine:

1. Adopt simultaneous adjustment for neighboring cadastral blocks:

Where adjacent sheets form a single cadastral fabric, they should be adjusted simultaneously using common points and boundary conditions rather than georeferenced independently. This approach directly addresses inter-block discontinuities and was found to reduce tie-point discrepancies substantially.

2. Strengthen and improve the distribution of Ground Control Points:

Future field surveys should emphasize reliable, well-distributed control around block boundaries and within block interiors. Additional observations should focus on areas with

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poor coverage or high residuals rather than simply adding more points where control is already good.

3. Improve the selection, distribution, and validation roles of tie points:

Tie points should be accepted only when both occurrences clearly represent the same cadastral vertex or physical feature. After verification, the accepted shared points should be divided into two spatially distributed subsets: Control Tie Points used to constrain the simultaneous solution and Check Tie Points withheld for independent inter-block validation. An incorrect Control Tie can propagate distortion through the network, whereas a poorly selected CTP can misrepresent validation performance. Both classes should therefore be distributed along the common boundary, including near its ends where possible.

4. Do not use RMSE as the sole criterion for model selection:

The selected transformation should also be assessed using independent Check Points, individual residuals, tie-point agreement, boundary continuity, and GIS inspection of parcel geometry, especially when using higher-order polynomial models.

5. Maintain independent Ground Check Point and Check Tie Point datasets:

Ground Check Points should remain excluded from parameter estimation and should be exported with their reference and transformed coordinates so that absolute external accuracy can be reproduced. In parallel, selected Check Tie Points should remain excluded from all shared-boundary constraints and should be exported with the coordinates calculated from each neighboring block in the independent and simultaneous solutions. Reporting both datasets provides complementary absolute and relative validation.

6. Add polygon-based topological validation:

Future applications should measure gap and overlap areas and compare parcel areas and shapes before and after adjustment. This would extend validation from pointwise boundary agreement to the integrity of the entire cadastral fabric.

7. Document and preserve surviving historical cadastral monuments:

Cadastral crosses, iron monuments, stone boundaries, and comparable permanent features should be surveyed, photographed, described, and archived because they provide an essential physical link between the historical record and the modern coordinate framework.

8. Preserve original and adjusted data together:

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The adjusted results should not replace the original sheets and coordinates. Both should be retained together with a complete record of accepted and rejected points, residuals, transformation models, and adjustment decisions to ensure traceability and facilitate future review.

9. Continue the development of MapGeoref:

The current version of MapGeoref already includes automated Check Point evaluation, Control Tie/Check Tie classification, CTP comparison reporting, experiment scenarios for transformation model and GCP-count sensitivity, matrix export, and GIS-oriented raster export. Further development should therefore focus on polygon topology testing, automated gap/overlap and parcel-area analysis, uncertainty propagation, more comprehensive and standardized reporting, and tighter integration with GIS platforms.

10. Validate the methodology in additional Palestinian study areas:

Before generalizing the numerical accuracy achieved in Tammun, the approach should be tested on other Jordanian cadastral sheets with different terrain, sheet conditions, control densities, and surviving field evidence.

11. Develop a standardized technical framework for historical cadastral rehabilitation:

Field control, historical-feature verification, tie-point selection, model selection, accuracy assessment, boundary validation, and preservation of original and adjusted datasets should be incorporated into a unified procedure.

12. Integrate geometric adjustment with established cadastral and legal procedures:

The corrected coordinates should be regarded as an improved technical basis for settlement, boundary re-establishment, and spatial analysis, but should not be treated as a substitute for official records or the legal adjudication of property rights.

13. Standardize sensitivity testing before operational adoption:

For each study area, repeat the adjustment using a controlled set of transformation orders and reduced-GCP scenarios while keeping the same independent Ground Check Points and Check Tie Points fixed. Report the resulting changes in combined network RMSE, Ground Check Point RMSE, CTP RMSE, and boundary-continuity indicators. This sensitivity test will indicate whether an apparent improvement is stable or depends excessively on model flexibility or control density.

References

References

- Bitelli, G. and Gatta, G., 2011. Experiences on georeferencing of maps from the XIX century Gregorian Cadastre of Bologna (Italy). *e-Perimtron*, 6(4), 270-275.
- Bolstad, P. V., Gessler, P. and Lillesand, T. M., 1990. Positional uncertainty in manually digitized map data. *International Journal of Geographical Information Systems*, 4(4), 399-412. <https://doi.org/10.1080/02693799008941555>
- Boutoura, C. and Livieratos, E., 2006. Some fundamentals for the study of the geometry of early maps by comparative methods. *e-Perimtron*, 1(1), 60-70.
- Bozzano, M., Sguerso, D., Zatelli, P., Zendri, D. and Besana, A., 2024. Accuracy evaluation for plan-reliefs and historical maps created during WWI in Northern Italy. *ISPRS International Journal of Geo-Information*, 13(3), 101. <https://doi.org/10.3390/ijgi13030101>
- Brovelli, M. A. and Minghini, M., 2012. Georeferencing old maps: A polynomial-based approach for Como historical cadastres. *e-Perimtron*, 7(3), 97-110.
- Cajthaml, J., 2013. Old maps georeferencing - overview and a new method for map series. In *Proceedings of the 26th International Cartographic Conference, Dresden, Germany*. International Cartographic Association.
- Cvijetinovic, Z., Avramovic, M. and Mihajlovic, D., 2015. Digital cadastral map as foundation of coordinate based cadastre of Serbia. *Survey Review*, 47(343), 241-255.
- Delfgou, C., Bakogiannis, N. and Laube, P., 2023. Uncertainty analysis of geodata derived from digital map processing. *International Journal of Geographical Information Science*, 37(7), 1667-1691. <https://doi.org/10.1080/13658816.2023.2206890>
- Enemark, S., Bell, K. C., Lemmen, C. and McLaren, R., 2014. Fit-for-purpose land administration (FIG Publication No. 60). International Federation of Surveyors.
- Food and Agriculture Organization of the United Nations (FAO)., 2012. Voluntary guidelines on the responsible governance of tenure of land, fisheries and forests in the context of national food security. FAO.
- Forejt, M., Dolejš, M., Zacharová, J. and Raška, P., 2020. Quantifying inconsistencies in old cadastral maps and their impact on land-use reconstructions. *Journal of Land Use Science*, 15(4), 570-584. <https://doi.org/10.1080/1747423X.2020.1765427>
- Gavish, D., 2005. *The survey of Palestine under the British Mandate, 1920-1948*. Routledge.

References

- Gavish, D. and Kark, R., 1993. The cadastral mapping of Palestine, 1858-1928. *The Geographical Journal*, 159(1), 70-80. <https://doi.org/10.2307/3451491>
- Ghilani, C. D., 2017. *Adjustment computations: Spatial data analysis*, 6th ed.. Wiley.
- Ghilani, C. D. and Wolf, P. R., 2012. *Elementary surveying: An introduction to geomatics*, 13th ed.. Pearson.
- Hagemans, E., Unger, E.-M., Soffers, P., Wortel, T. and Lemmen, C. H. J., 2022. The new, LADM inspired, data model of the Dutch cadastral map. *Land Use Policy*, 117, 106074. <https://doi.org/10.1016/j.landusepol.2022.106074>
- Havlíček, J. and Cajthaml, J., 2014. The influence of the distribution of ground control points on georeferencing. *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management*, 3(2), 965-972.
- Heiskanen, W. A. and Moritz, H., 1967. *Physical geodesy*. W. H. Freeman.
- Hofmann-Wellenhof, B. and Moritz, H., 2006. *Physical geodesy*, 2nd ed.. Springer.
- International Association of Oil and Gas Producers (IOGP)., 2026. *EPSG Geodetic Parameter Dataset*. <https://epsg.org/>
- International Federation of Surveyors (FIG)., 1995. *The FIG statement on the cadastre* (FIG Publication No. 11). International Federation of Surveyors.
- Janata, T. and Cajthaml, J., 2021. Georeferencing of multi-sheet maps based on least squares with constraints - First Military Mapping Survey maps in the area of Czechia. *Applied Sciences*, 11(1), 299. <https://doi.org/10.3390/app11010299>
- Jordanian Lands and Survey Department., 1963. [Historical cadastral survey records and mapping instructions]. Amman, Jordan.
- Kral, U., Sönmez, E. C. and Reimer, F., 2021. Data description of “City boundary and urban district boundaries, Vienna, 1920”. *Data in Brief*, 38, 107382.
- Lemmen, C., van Oosterom, P. J. M. and Bennett, R. M., 2015. The Land Administration Domain Model. *Land Use Policy*, 49, 535-545. <https://doi.org/10.1016/j.landusepol.2015.01.014>
- Longley, P. A., Goodchild, M. F., Maguire, D. J. and Rhind, D. W., 2015. *Geographic information science and systems*, 4th ed.. Wiley.
- Luft, J. and Schiewe, J., 2021. Automatic content-based georeferencing of historical topographic maps. *Transactions in GIS*, 25(6), 2888-2906.
- Mikhail, E. M., Bethel, J. S. and McGlone, J. C., 2001. *Introduction to modern photogrammetry*. Wiley.

References

- San-Antonio-Gómez, C., Velilla, C. and Manzano-Agugliaro, F., 2015. Photogrammetric techniques and surveying applied to historical map analysis. *Survey Review*, 47(341), 115-128. <https://doi.org/10.1179/1752270614Y.0000000098>
- Schowengerdt, R. A., 2007. *Remote sensing: Models and methods for image processing*, 3rd ed.. Academic Press.
- Sengupta, A., Lemmen, C., Devos, W., Bandyopadhyay, D. and van der Veen, A., 2016. Constructing a seamless digital cadastral database using colonial cadastral maps and VHR imagery: An Indian perspective. *Survey Review*, 48(349), 258-268. <https://doi.org/10.1179/1752270615Y.0000000003>
- Sisman, Y. and Sisman, A., 2017. The factors optimization on georeferencing analogue maps. *Arabian Journal for Science and Engineering*, 42, 2471-2478. <https://doi.org/10.1007/s13369-016-2353-6>
- Snyder, J. P., 1987. *Map projections - A working manual* (U.S. Geological Survey Professional Paper 1395). U.S. Government Printing Office.
- Tamim, N. S. and Taha, A. A., 2016. Assessment of geometric accuracy of Jordanian cadastral maps in the West Bank-Palestine. *Journal of Engineering Research and Technology*, 3(4), 98-107.
- Tammun Settlement Project - Phase Two Field Reports., n.d.. Field documentation used for the selected cadastral blocks. Unpublished project records.
- Tucci, M. and Giordano, A., 2011. Positional accuracy, positional uncertainty, and feature change detection in historical maps: Results of an experiment. *Computers, Environment and Urban Systems*, 35, 452-463. <https://doi.org/10.1016/j.compenvurbsys.2011.05.004>
- United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM), 2020. *Framework for effective land administration*. United Nations.
- Williamson, I., Enemark, S., Wallace, J. and Rajabifard, A., 2010. *Land administration for sustainable development*. ESRI Press Academic.
- World Bank., 2008. *West Bank and Gaza: Second Land Administration Project*. World Bank.
- World Bank., 2019. *West Bank and Gaza: Real Estate Registration Project*. World Bank.
- Younis, G., 2015. Practical method to solve large least squares problems using Cholesky decomposition. *Geodesy and Cartography*, 41(3), 113-118. <https://doi.org/10.3846/20296991.2015.1086118>

References

- Younis, G., 2020. The effect of using multiple coordinate systems and datum transformations on the calculated coordinates in Palestine. *Bulletin of Geography. Physical Geography Series*, 19(1), 31-41. <https://doi.org/10.2478/bgeo-2020-0008>
- Younis, G., Qafisheh, M., Ideas, S., Abu Shara, O. and Maraheel, M., 2025. The development of the Geodetic Reference Frame of Palestine (PAL-GRF2023). *Engineering for Palestine Conference*, Palestine Polytechnic University.