IMPROVING THE COMMUNICATION OF

WATER ALLOCATION DECISIONS USING INTERACTIVE MAPS

by

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ABSTRACT

There is a finite amount of fresh water available for use by water users (geologic processes, plants, animals, and even humans). Thus, conflicts and disputes often arise over water allocation, especially in the western United States, where water reserves are already scarce. Water rights systems and policies are designed to allocate water fairly even when water runs short. However, the science and legal principles behind these water rights systems are difficult to communicate to stakeholders, leading to reduced participation and legitimacy of policies (Priscoli 2004; Reisner 1993). Earlier work suggests that interactive maps can support or enhance stakeholder knowledge creation or refinement by promoting exploration of map data (MacEachren 2000; MacEachren and Brewer 2004; Andrienko and Andrienko 1999). This study explores approaches to visualizing water rights policies at multiple scales in communities and landscapes of the Ruby River Basin in Montana. A series of interactive maps was created and shared with stakeholders to obtain feedback based on expert local knowledge. The results suggest that interactive maps are powerful vehicles for communicating water right policies to stakeholders if careful attention is paid to applying cartographic design principles in maps properly contextualized for local conditions. Results also suggest that interactive maps are particularly useful in multiple representations of data that cannot be conveyed effectively through symbology. Future research is needed to test whether such maps actually improve stakeholder knowledge and perception, and in turn spur public participation.

CHAPTER 1: INTRODUCTION

1.1 Topic Definition

There is a finite amount of fresh water available for use by water users (plants, animals, and even humans). Since human society and the environment both rely on fresh water for their survival, they must compete to use it. Consequently, political conflicts often arise when one individual or group receives a larger share of water than another does, even when decisions comply with the law and due process.

1.1.1 Sources of Water Conflict

Some political conflicts are centered over how water is used (e.g. agriculture, recreational, or industry) and how water is stored and transported. As an example, federal regulators clash with water users over acceptable levels of pollutants (e.g. fertilizers and industrial waste) that can be discharged into rivers or lakes without affecting water quality for other uses, like drinking, fishing, or swimming (Gerber and Poticha 2008; U.S. Environmental Protection Agency n.d.).

Other conflicts focus on how water is stored. As the rate of diversion from natural water sources began to exceed their recharge rates, dams and other hydrologic infrastructures were developed by the government to manage the quantity and quality of water. The use of these structures has dramatically increased our ability to live in previously uninhabitable areas, such as the arid regions of the western United States (Reisner 1993). Even so, their use and development has been controversial. An argument over construction of the Parker Dam resulted in deployment of the Arizona National Guard in 1934 (U.S. Department of the Interior n.d.).

Despite the benefits of these technological advances, they have not increased the total amount of water available to water users. Although water stored in dams can be released for permitted uses during periods of drought, Las Vegas is spending $800 million to build a new drinking-water intake for Nevada's Lake Meade that can accommodate projected diminishment of water flows from Utah's Lake Powell reservoir (Hollenhorst 2012). Lower water levels in the Western U.S. may become a reality soon due to increased temperatures and reduced rainfall accumulations associated with climate change (Anderson and Woosley 2005). Against this backdrop, it is clear that equitable allocation is critical to the successful management of surface water resources.

1.1.2 A Solution for Allocating Water

In the United States, each state has developed a legal system, composed of policy, law, science, and technology to allocate and distribute water. These are commonly called water rights systems. Most western state water rights systems require users to obtain a permit from the state to divert (i.e., "appropriate") water from a public source for beneficial uses. When resources run low, junior permit holders are required to stop using water to conserve water for senior claims based on the permit, or priority date, a concept known as "first in time, first in right", or the *prior appropriation doctrine*. Permitted uses vary among states but often include "consumptive economic uses" like agriculture (Cosens 2009; Matthews et al. 2001). The goal of this study is to explore what roles maps and geographic information systems (GIS) might play in improving the communication of water allocation decisions made under these water rights systems to stakeholders.

1.2 Motivation

Many water rights systems are run using a combination of paper and legacy computer systems, which can prove troublesome, for both water users and administrators (Morse 2005; Solum 2005). Inefficient paper-based record-keeping systems can increase the time needed to make allocation decisions or resolve disputes, resulting in frustrated and confused stakeholders. Computerized decision support systems are not much better if they rely on obsolete computer code, methods lacking scientific rigor, or incomplete models of policy rules. These systems can be difficult to update in order to address emerging challenges such as the practice of "water banking" (Barringer 2011).

A second obstacle to equitable allocation is that decision-makers do not always clearly explain the policies that govern water allocation decisions and water rights systems. To be fair, some systems and policies are designed under a theory that a group of experts relying on law and science can make better, more efficient decisions than stakeholders could through participation (Molle 2004; Yates 1982). Nevertheless, a poor understanding of water rights systems or policies decreases stakeholder participation and increases the number of decisions whose equity is disputed (Priscoli 2004). As water becomes scarcer, increased stakeholder understanding is critical to ensure that equitable allocations are made, whether by a group of experts or through participation.

Several GIS methods have been developed to address design challenges that contribute to inefficient or erroneous administration of water rights (Allen et al. 2005; Morse, et al. 1990; Sheng and Wilson 2009; Wurbs 2005). This study explores methods for improving communication of water right policies to stakeholders.

1.3 Study Overview

To explore ways to increase stakeholder understanding, this study developed a portfolio of interactive maps using a geospatial PDF format. The interactive maps visualize the historical allocation of water under the prior appropriation system commonly used in the western United States, and demonstrate the role of beneficial use under that system. Several individuals with expert local knowledge of water rights and allocation decisions provided feedback on the cartographic design, technical content, and interactive features (i.e., the ability to toggle visibility of layers in the geospatial PDF map format) of the portfolio.

Evaluating the interactive features is important because there are few examples in the literature (Cervantes 2009) and none with water resource applications. Dix and Ellis (1998) offer one of the earliest arguments for including interactivity in maps. In essence, they argue that adding interactivity adds value to an existing visualization method, whether it is two-dimensional maps or three-dimensional pie charts. For example, they suggest that the ability to click on an element of a stacked histogram, have the other elements “sink”, and extend below the baseline makes it easier to perceive relationships between that particular element and the others.

1.3.1 Study Area

The study focused on the Ruby River drainage basin in Montana, a prior-appropriation state with characteristics that have contributed to serious water disputes in the recent past. The state contains a land area of 145,546 square miles and a population of 989,415 (U.S. Census Bureau 2012).

The Ruby River drainage basin is located in the Missouri River hydrologic region in southwestern Montana (Figure 1). The state is known for its natural beauty, and draws numerous many visitors to its two national parks, Glacier National Park and Yellowstone National Park. Other historic economic activities include logging, mining, fishing, and agriculture (Diamond 2004).

Like many Western states, the state's climate is generally arid and experiences low annual rainfall levels. Therefore, the use of dams and intensive irrigation has played an extensive role in the state's ability to support both its natural and human populations and produce crops (Reisner 1993). Although water rights were claimed as early as the 1800s, a formal water rights system was not established until 1972, making it tough to verify the accuracy of these claims (Legislative Environmental Quality Council 2009).

The Montana Department of Natural Resources (DNRC), which administers the water rights system, has divided the state into several drainage basins whose boundaries closely correspond to those of the United States Geological Survey's Fourth-Level Coded Hydrologic Units (HUCs) (U.S. Geological Survey 2012). Fourth-Level HUCs provide a standard representation of river sub-basins. Each sub-basin is divided into Fifth-Level HUCs that represent individual watersheds.

The DNRC identifies the Ruby River drainage basin as area 41C (Figure 1). It was selected as the study area for this study because of its small size and manageable number of water rights. The Ruby River drainage basin has an area of 973.3 square miles (622, 974 acres) and is lightly appropriated relative to other drainage basins in Montana (Ruby Valley Conservation District and Ruby Valley Watershed Council 2012).

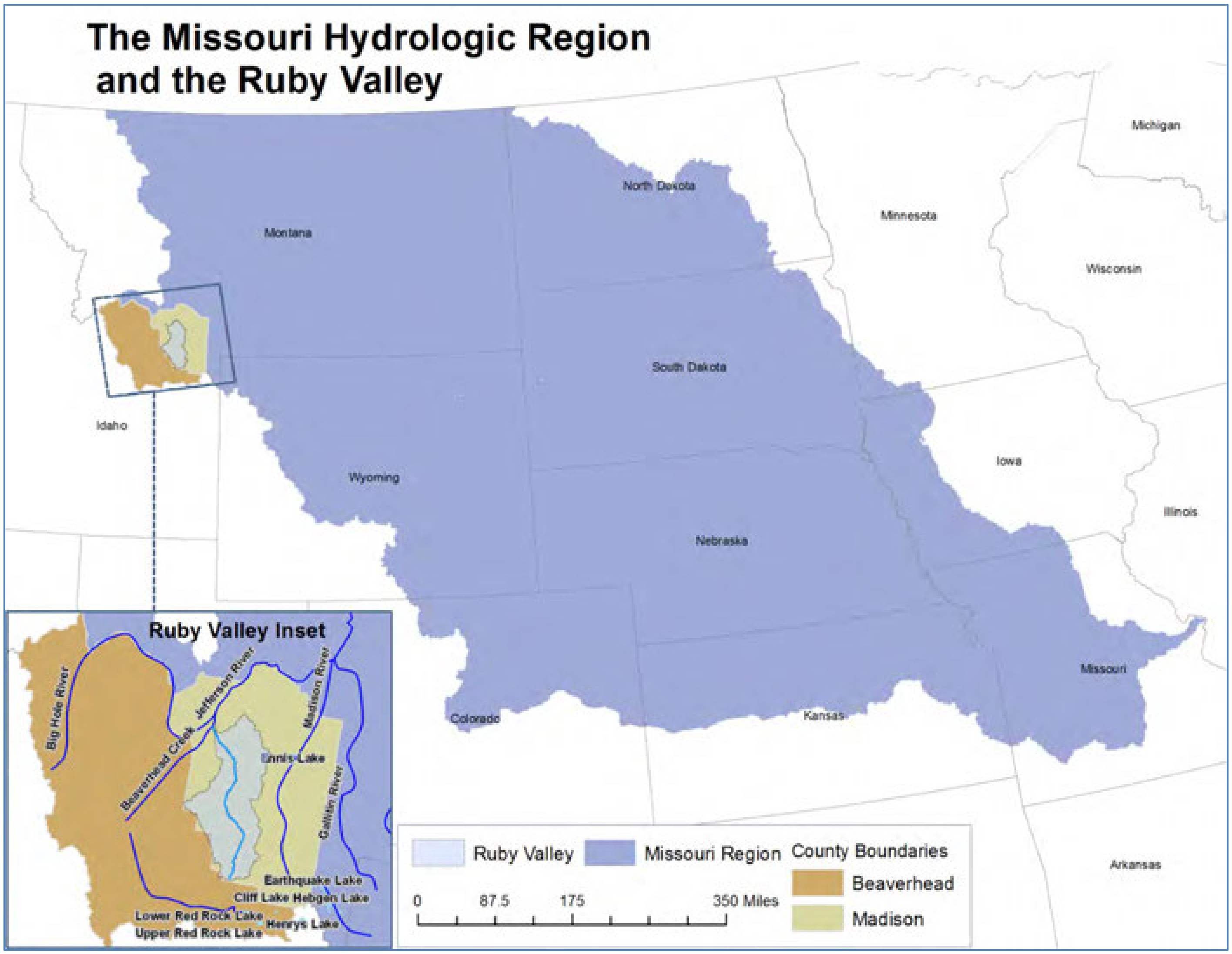


Figure 1 Map of the Missouri Hydrologic Region and Ruby River Drainage Basin

Within the drainage basin, there are currently 4,321 unique active water rights, of which 2,471 are diverted from surface water resources (Montana State Library 2012). For perspective, one heavily appropriated sub-basin within the 40J drainage basin, located in northeastern Montana, contains at least 7,000 surface water rights (Stickney et al 2010) and the Clark Fork river basin contains 26,274 surface water rights spread across eight drainage basins (Shively and Mueller 2010). In concentrating on the Ruby River basin, the case study focuses less on data processing, and more on developing solid methods for visualizing water rights

CHAPTER 2: BACKGROUND

Section 2 reviews existing research on the role of beneficial use in allocation decisions and stakeholder understanding of a water rights system. The review assesses how interactive maps can potentially help stakeholders better understand policies of water allocation decisions, providing a theory for how stakeholder understanding might be increased. The historical tension between democracy and efficiency in American government policymaking is described using a model from Yates (1982). This model serves as an organizational framework for the review. Following the discussion of Yates (1982), the review provides definitions for beneficial use and water rights. Then it explores how beneficial use and water rights influence allocation decisions. Next, it discusses the need for stakeholders to understand these decisions. Finally, potential roles for GIS in water allocation decisions are reviewed and their connection to stakeholder understanding of water allocation decisions is established. This section concludes by summarizing the purpose of this study and the hypotheses in this particular context.

2.1 Theories of Public Participation

Two competing theories have historically driven the creation of American government and the formation of stakeholder policy: pluralism theory and efficiency theory (Yates 1982). These theories are relevant for understanding how public participation is included in water right policy development and program administration. They also influence how GIS is used to communicate information about water right policies and programs to stakeholders. The following section discusses their definitions and impact on stakeholder policies and programs.

2.1.1 Pluralism and Efficiency

Pluralism theory envisions a constitution and democratic government structure in which power is distributed among multiple competing groups. Stakeholder participation is important to ensure the groups check and balance each other. This theory was developed in opposition to the practices of Britain, and grounded in two beliefs: (1) distributing power throughout government structure reduces the risk of corruption; (2) politicians and citizens are the best administrators or policymakers in a democratic society while presidents and kings are not to be trusted. By creating a government with access for stakeholder participation and competing power centers, proponents of this theory believe that all stakeholder and minority interests would have an equal voice in creating policy. Through compromise and negotiation, the resulting government policy accommodates the greatest number of interests (Yates 1982).

Efficiency theory envisions a system in which government operations are removed from messy politics. A strong executive with centralized power and control presides over operations run by a cadre of specialized, nonpolitical, professional experts and analysts who efficiently administered policies based on rational thought, science, and law (Yates 1982). In efficiency theory, stakeholder interests are discovered through expert judgment of their needs rather than through negotiation between competing interest groups.

The theories are in tension with each other (Yates 1982). Pluralists worry about corruption and misuse of power under a centralized government structure and restrictions on stakeholder participation in policy development and program administration.

Efficiency proponents believe that distributed power, excessive stakeholder participation, and policy development through negotiation lead to a fragmented government that is inefficient, fiscally irresponsible, and unable to address stakeholder needs in a timely manner. The result is a hybrid government that at times demonstrates the best and worst of these theories. The rest of this review illustrates how these theories affect water policies and stakeholder participation in allocation decisions.

2.1.2 Approaches to Beneficial Use and Water Rights Allocation

In response to the increased potential for resource conflict and unauthorized diversions from natural and artificial water sources, state governments implemented *prescriptive* systems of water rights with market-based approaches to allocation. These were similar to other property right systems already in use, such as real estate (Johnson et al. 1981). The features of this approach resemble those from the efficiency approach to government, including rational, efficient allocations based on law and science (Yates 1982). For example, the Montana Water Use Act of 1973 (Doney and Noble 2010) enumerates the permitted beneficial uses for which water can be allocated under that state's water rights system. The prior appropriation doctrine determines the seniority of a claim based on the date when water was first legally diverted under the claim, also known as the priority date. The Act was established during the 1972 Montana Constitutional Convention (Legislative Environmental Quality Council 2009). Prescriptive approaches are presumed to be fair and impartial since they rely on science, law, rational thought, and non-political, highly educated civil servants (Yates 1982).

Unfortunately, the scientific and legal complexity of prescriptive approaches may prevent water users from challenging the equity of disputed decisions. In addition, prescriptive approaches limit independent verification of models, methods, and assumptions, which may result in incorrect calculations of water availability based on inappropriate models or overly optimistic assumptions (Priscoli 2004). Molle (2004) asserts that prescriptive approaches used by government bureaucracies often reflect the power structures and distributions in society and give preference to water users with greater social or political status. As a result, methods that determine permitted beneficial uses often promote traditional economic interests, such as agriculture, over other uses. (Matthews et al. 2001).

Moreover, these approaches do not easily accommodate alternative methods or values used to determine equity (Postel 2008). Common examples include (1) historical pluralistic agreements within a water community, (2) moral or religious beliefs, (3) concern for threatened ecosystems, plants, or animals (Molle 2004; Brown 2004; Pradhan and Meinzen-Dick 2001). The resulting inflexibility and potential inequity of prescriptive approaches can lead to lawsuits, polarization, and a tendency to dispute resource conflicts rather than resolve them (Norton 2005).

In contrast, *negotiated* rights are developed between individual or group water users, gradually and iteratively, over a longer temporal period, based on available resources and collective needs. This system is more informal than prescriptive approaches and specific to a community of users. Consequently, the negotiated rules may vary between communities within a region and between regions.

Likewise, as the needs of a water user community grow and change, new rules may be established and existing rules modified on a regular (e.g. monthly, annual, or very decade) or ad-hoc basis.

State agencies are not usually involved since the user community assumes responsibility for development of water allocation rules, definition of permitted beneficial uses, and maintenance of negotiated rights. When the state becomes involved, it usually serves as a mediator between user groups, rather than as an administrator or enforcement agent (Molle 2004). As with the pluralist approach to government, negotiated rights emphasize stakeholder participation and policy development through negotiation or bargaining (Yates 1982).

Pluralistic approaches appear to overcome many flaws of their prescriptive counterparts. The negotiation-based approach encourages transparency and inclusion of multiple values and interests (Pradhan and Meinzen-Dick 2001). Since all parties participate in the development of decision criteria and rules, this approach promotes mutual awareness, agreement, maintenance, and enforcement by all parties and reduces conflict resulting from misunderstanding the rules (Trawick 2002). Moreover, rules, policies, and models can be further refined to improve water availability and quality as knowledge of the geographic area's hydrology, climate, and environment is collectively shared and distributed within the water community. Developing rules and models used to allocate and enforce water rights using an entire community's knowledge may be superior to a prescriptive approach's sole use of science-based quantitative knowledge, which can be incomplete or inaccurate (Molle 2004).

Despite these benefits, pluralistic approaches have their setbacks. They can be affected by inequities or power imbalances within a community's culture and societal norms, although the negotiation-based process may offer a method for resolving them. Moreover, adoption of a pluralistic approach requires a much higher level of community interest, participation, knowledge sharing, money, and time to implement (Molle 2004).

In summary, neither approach to water allocation decisions is perfect. Despite their inflexibility and potential for inequity in allocation decisions, prescriptive approaches are widely used today by bureaucratic governments. Even so, pluralist approaches are gaining popularity because of their inclusive, flexible, negotiation-based approach and greater support for stakeholder education and participation.

2.2 GIS Roles and Allocation Decisions

Under both the prescriptive and pluralistic approaches, water right administrators face many challenges. Geographic information systems (GIS) can act as a powerful tool for managing water allocation decisions (Tsihrintzis et al. 1996). The predominant role of GIS in water rights is providing decision-support to administrators. The current study explores an emerging role for GIS as a tool for visualizing policies. This section provides examples of each role, discusses how they support public participation, and provides a theoretical framework for this study's methodology.

2.2.1 GIS as a Decision Support Tool

The Texas Water Rights Analysis Package (WRAP) was designed to model water availability, improve water management decisions, and make the Texas water permitting system more efficient (Wurbs 2005).

WRAP calculates estimates using hydrologic parameters and control points for each river basin assessed. It relies on two independent models to calculate natural stream flows (WRAP-HYD) and simulate their appropriation (WRAP-SIM). Simulations performed with this software are based on Texas water right regulations under one or more management scenarios, such as varying degrees of drought (Wurbs 2005). The simulation results provide the amount of un-appropriated water remaining for future water right claims and several summary statistics (Wurbs 2005).

Developing comprehensive decision support systems is a complex process because of the need to model a large number of variables. WRAP modeled water rights regulations, water use agreements, compacts, permits, hydrologic storage, transport, flow parameters, and many other parameters (Wurbs 2005). Since the funding and expertise to develop such systems is not always available, most research focuses on development and implementation of GIS tools and methods to address individual components of a comprehensive decision support system.

Rosenthal et al. (1995) describe how the Geographic Resource Analysis Support System (GRASS) was linked to the Surface and Water Assessment Tool (SWAT), a popular hydrological model, for a continuous simulation of water quality assessments on the Lower Colorado River Basin in Texas (Neteler et al. 2012; Neitsch et al. 2002). This reportedly reduced the time needed to develop the large amount of input data and parameters required for an assessment at the river-basin scale.

Sheng and Wilson (2009) describe a recent example of integrating the MIKE-BASIN hydrological model to ArcGIS in order to perform a water quality and watershed health assessment for the Santa Monica Bay Watershed in Southern California. This integration allowed the researchers to perform hydrology and water quality simulations with MIKE-BASIN while letting ArcGIS and the ArcHydro extension (Maidment 2002) handle data management and visualization tasks (Sheng and Wilson 2009).

One challenge that developers of tools like WRAP, SWAT, or MIKE-BASIN face is collecting data to calculate input parameters. When parameters cannot be derived from a high-quality dataset at a scale appropriate for the study, they are estimated from general equations and regional models. The problems of estimation are documented in the literature (Inskeep et al. 1996; Macur et al. 2000; Lindahl, et al. 2008; Clark 1998).

Allen et al. (2005) describe one remote sensing model, Mapping Evapotranspiration at High Resolution and with Internalized Calibration (METRIC), for calculating evapotranspiration (ET) on irrigated land. Measurement of ET from irrigated land allows states to assess whether they comply with legal compacts and agreements that specify how many hectares they can irrigate using water diverted and allocated from a shared resource. Evaporation measures water that is absorbed from earth's surface, over land or water. Transpiration is what evaporates from plants on the landscape. Evapotranspiration, a component of many water-balance models, is a composite measurement of both evaporation and transpiration from the earth's surface.

Using METRIC, the Idaho Department of Water Resources (IDWR) calculated ET on the Bear River in eastern Idaho using Landsat satellite imagery.

The improved quality of the ET calculations resulted in refined estimates of rates for groundwater flow, groundwater recharge, and crop yield. Improved estimates led to increased enforcement of water shut-off orders and water allocation limits under water right permits (Allen et al. 2005).

Morse et al. (1990) describe another application of GIS and remote sensing to support the adjudication of water rights in Idaho's Snake River Basin. The intent of the project was to create an accurate dataset of land-cover that would enable water rights administrators to calculate the acreage of each land cover class per quarter-quarter section, the smallest spatial unit legally describing water rights claims in Idaho using the Public Land Survey System (PLSS). A remote-sensing package was used to create a land-cover dataset showing six different classes, including irrigated land. GIS was used to digitize the PLSS from 1:100,000 scale Mylar maps and then overlay it on top of the Landsat classification grid. This overlay allowed the Idaho Department of Water Resources to calculate the acreage of each land cover class for each quarter-quarter section. Morse et al.(1990) used regression analysis methods to estimate the accuracy of the Landsat land-cover classification and reported an average r^2 of 0.90 for the first five counties, indicating a good linear fit between classified and actual land cover values.

2.2.2 GIS as a Visualization Tool

GIS-based decision-support tools have improved some of the technical problems that contribute to inefficient and error-prone water rights systems, but suffer from a common shortcoming: They are designed, developed, and implemented without awareness of how they affect a stakeholder's understanding of the decision process.

A newer GIS role that incorporates this awareness requires the visualization of water right policies. Many water resource management decisions are challenged because water users question their equity and fairness. In part, decision equity and parity is influenced by the competing efficient or pluralistic approaches to government structure and prescriptive or negotiated policy for allocating water rights (Yates 1982; Molle 2004). Additionally, stakeholders often do not understand the decision process, underlying methods, or data, leading to concerns about its equity and lack of interest in increasing their scientific knowledge (Priscoli 2004).

Some scholars argue that research should be directed towards developing "spatial understanding systems" that communicate the structure, policy, and rationale behind decisions rather than acting as decision support systems (Ramsey 2009; Couclelis and Monmonier 1995; Elwood 2006). They argue that GIS has the power to visualize decision results and the deliberation process through maps. Consequently, visualizing water allocation decisions with GIS would go a long way towards improving stakeholder understanding and participation.

The water allocation decision process is inextricably linked to an underlying community of users who embed the social value of water in their culture (Pradhan and Meinzen-Dick 2001), a social and administrative structure for managing water rights (Yates 1982; Molle 2004) and, ultimately, the physical structure of the landscape with which water resources and users interact (Cosens 2009). Visualizing these complex relationships and interactions using GIS is likely to be far more efficient and powerful than describing them in narrative text.

There are five different types of resource ownership for most water rights systems in the United States (Matthews 2004) or twelve permitted beneficial uses of water in the state of Montana (Legislative Environmental Quality Council 2009). What may be more useful to a stakeholder is visualizing where these characteristics of water right claims occur on the landscape with respect to other features. For example, examining the proximity of places where water is used for irrigation to the locations of farms may help stakeholders better understand who uses water diverted for this purpose.

Matthews et al. (2001) highlight another important spatial relationship between the direction of water flow in a river basin based on gravity and the hydrological regime, and the historical allocation of that flow under a "prior appropriation" system. Surface water generally flows downstream from higher to lower elevations. In contrast, over time, points of diversion used to appropriate water from a river or other source can mimic the downstream flow, move upstream in the opposite direction, or in both directions at once.

Thus, the temporal hierarchy of water right claims may not match the physical hydrological structure, resulting in cases where a junior appropriator may be upstream from a senior appropriator. In a period of drought or water shortage, this junior appropriator may be confused as to why they must let water flow freely by their diversion structure to satisfy the needs of the downstream senior appropriator unless this fact is clearly explained to them. Likewise, the complexity of these "mismatches" may be frustrating to claim examiners attempting to determine whether to deny a new or amended permit application because it injures the rights of other existing appropriators along the same river or water source.

In both cases, a map that symbolizes diversion points, using their appropriation date and the direction that water flows over the landscape, may be a useful vehicle not only for clarifying these relationships but also for communicating decisions to permit applicants.

The scenarios provided above demonstrate why mapping the allocation and use of water resources under a water rights system may be useful for improving stakeholder understanding of allocation decisions. In a recent report, MacEachren (2000) suggests a two-part process for developing visualization tools that support collaborative decision-making processes. First, a theoretical framework should be developed to model the decision-making process and identify the relevant support roles for GIS. Second, GIS applications should be extended or developed in order to fulfill that role. Several models of the decision-making process can be found in recent papers (MacEachren and Brewer 2004; Armstrong and Densham 2008; Jankowski and Nyerges 2001)

Of these, Maceachren and Brewer (2004) offer the most detailed description, including several roles for GIS. They divide their framework into two parts that describe: 1) the human components of the decision-making process, and 2) the computing infrastructure available. First among the human components is the problem context of the decision-process, which the authors enumerate as *knowledge construction or refinement* (i.e., learning something from data), *conceptual design* (i.e. designing something, e.g. a park), *decision-support*, or *training and education*. They also enumerate the collaboration tasks required of the group during the process, namely *brainstorming, refining, selecting,* and *executing* a solution.

Finally, the authors describe the group's mutual perspective on the decision process as either *cooperative* or *conflicted*. Each perspective has a goal of communicating shared understanding or resolving conflicts through negotiation (MacEachren and Brewer 2004, 7–8).

Within the human and computational environment, Maceachren and Brewer (2004) suggest two potential visualization roles for GIS, which vary slightly depending on individual situations. First, GIS can provide a shared representation of an object or concept (e.g. water rights) that allows collaborators to explore the data together and thus promotes brainstorming, analysis, and negotiation of ideas, perspectives, and solutions related to it. Second, GIS can provide an illustration of the decision-making process itself, allowing collaborators to visualize their role in the process as well as its outcomes.

The first component of the computing infrastructure is the spatial and temporal context of the process. Group members can collaborate at a distance or within the same space, either asynchronously or in real-time. These spatial and temporal contexts affect the choice of tools used to support the decision process. The second component is the interaction characteristics of the stakeholders, including: the size of each group and potential sub-groups within them, the topology of connections between individuals, and technical or social constraints on information form and flow between collaborators (MacEachren and Brewer 2004, 9–10).The authors conclude by applying the framework to two case studies where GIS was used and highlight how current software limitations constrain the usefulness of GIS for assisting stakeholders in making decisions.

Both case studies explored geo-visualization applications for group exploration of spatio-temporal environmental data. The first study used a desktop-based tool for visualizing and animating data in 2.5 dimensions. The second study used a "semi-immersive" large screen to integrate three-dimensional space-time views of environmental data (MacEachren and Brewer 2004, 17).

It is clear that in previous studies, GIS has helped address some of the technical and scientific deficiencies of existing water rights systems by enhancing data collection, modeling hydrological processes, and providing decision-support (Morse et al. 1990; Sheng and Wilson 2009; Wurbs 2005). Even so, these existing applications have not improved administrators' ability to communicate decision processes to stakeholders. The next section describes a method used in the case study for this research to investigate the ability of GIS to improve the communication of water allocation decisions by visualization of water right policies.

CHAPTER 3: METHODOLOGY

The barriers to communication and understanding inherent in existing water rights systems hamper the ability of water resource administrators to resolve issues of decision equity. This is especially true for prescriptive water rights approaches, such as prior appropriation systems used in the Western United States. The research question underlying this study is: "Can GIS enhance the communication of water allocation decisions to stakeholders?"

In Montana, information on the structure and process of water allocation decisions is available to stakeholders in the form of a written document (Legislative Environmental Quality Council 2009). Visualizing this information through maps could be far more accessible to stakeholders because it connects abstract systems of permits, policies, and rules to the landscapes, people, and environment to which they apply. In other words, "*It is this ability to link the territory with what comes with it that has made maps so valuable to so many for so long"*(Wood and Fels 1992, 10).

This study strives to visualize several components of water allocation decisions (e.g. beneficial use or prior appropriation). Following Maceachren and Brewer's (2004) conceptual framework of GIS roles in group decision-making processes, this study hypothesizes that visualizing these components of water allocation will support a stakeholder's ability to *refine or create knowledge* of water right policies in Montana. To test this claim, several interactive maps were created to illustrate the role of these components in water allocation decisions. These maps were shared with stakeholders with expert, local knowledge of water rights and the study area.

The stakeholders evaluated and provided feedback on the maps' ability to support the creation and refinement of knowledge related to water allocation decisions.

3.1 Themes of Water Allocation Decisions

For this study, a series of spatial layers that represent selected components of water allocation decisions were compiled. These layers were used to create several interactive thematic maps that visually communicate the components to stakeholders in order to improve their understanding of water allocation decisions. The first step in developing these maps was to enumerate the water allocation themes that they represented so that they could be developed appropriately. Several individual themes come first, followed by combinations of those themes that illustrate their inter-relationships.

3.1.1 Upstream Appropriation Affects Downstream Users

This thesis, while focused upon the Ruby River drainage basin in southwestern Montana, cannot discuss it in isolation. Water flows from this drainage basin as the Jefferson River and joins with the Madison and Gallatin rivers to form the Upper Missouri Headwaters. The Missouri River itself then traverses north and east through much of Montana and parts of North and South Dakota and Nebraska before entering the Mississippi River at St. Louis, Missouri (Missouri River Natural Resources Committee and US Geological Survey, n.d.). Therefore, excessive appropriation of water resources within the study area can reduce water availability for downstream users, not just in Montana but also in other states. Thus, illustrating the connection between the study area and downstream communities within the largest common watershed is important.

3.1.2 Water Rights Reflect the Values of a Place

During the process of developing water rights, rules are established for how water is used by the community of users, otherwise known as "beneficial uses". Visualizing water rights on a map may help stakeholders better understand allocation decisions by telling a story of how a community uses water, both historically and in the present. For example, if water used for irrigation is located close to farms or open fields, this may illustrate the primary users of water for that purpose. Similarly, showing where water is currently used in relationship to where it comes from may show what forms of transportation are used to deliver that water from source to destination. Finally, showing how the pattern of beneficial use has changed over time may provide insight to stakeholders on the historical development of that community of water users.

3.1.3 Water Rights Have a Hierarchy

If beneficial use were the sole determinant of a claim to use water, there would still be conflict over whose beneficial use was more important. In the western United States, as previously stated, most water rights systems have resolved this conflict by using time to determine whose use is more important, otherwise known as the doctrine of "prior appropriation" (Matthews et al. 2001).

Under these systems, appropriators whose claims were recognized first have greater priority over those appropriators with later claims. Thus a farmer whose claim was established in the year 1975 would have a claim over a mining company whose claim was established in 1995, regardless of whether its beneficial use was deemed more useful or not.

Likewise, if an appropriator would like to file a new claim or change an existing claim, they must demonstrate that the new or amended claim does not harm the rights of existing senior appropriators.

3.1.4 Water Rights are Linked to a Physical Landscape

Water rights link to physical locations on the earth where water is diverted from a source and put to use. The location of water rights is determined in part by where water can be diverted, the community that uses it, and the story of a place in time.

Visualizing water rights on a map shows how the landscape ties these aspects together. For example, overlaying surface hydrology and the appropriation of water over time may show how the hierarchy of water right claims does or does *not* match the direction of hydrological flow over the landscape (Matthews et al. 2001). Furthermore, visualizing beneficial use and the hierarchy of water right claims may demonstrate how conflicts over the use of water are settled using the date of appropriation. Finally, visualizing beneficial uses of water in relation to the community of users may reveal to stakeholders any disagreement or disconnect in the social value of water between the community and the state.

Using this model to explore these aspects of beneficial use and water rights may inspire stakeholders to discuss the ethics and equity of allocation decisions, increase their cumulative understanding, and potentially move them to collaborate on a solution to any perceived inequities. This addresses the concerns of several scholars in the literature on the use of GIS to enhance stakeholder knowledge of water allocation decisions (Elwood 2006; Priscoli 2004; Postel 2008; Matthews et al. 2001).

3.2 Creating the Maps

The maps created for this study are limited in scope to visualizing water rights and beneficial use, relying solely on the free GIS datasets made available through the Montana GIS Portal. This allows the method to be easily repeated within the state and avoids time and cost constraints associated with extracting data from remote-sensing or hardcopy sources. Even so, creating defensible and informative maps that clearly visualize and communicate water allocation decisions to stakeholders requires attention to both technical and cartographic detail. The first step to creating the maps was to identify appropriate layers for use in their development.

3.2.1 Selecting Model Layers

To effectively communicate the role that beneficial use plays in water allocation decisions, two different types of layers must be selected: thematic and reference. Thematic layers focus on geographic features and phenomena related to water allocation, such as water rights or surface hydrology. Reference layers provide context to a stakeholder or other map viewer, helping them situate thematic layers on the landscape. Table 3-1 lists the thematic layers and Table 3-2 lists the reference layers selected for this model and describes their purpose in the model. Each layer was chosen and assessed based on its completeness, geographic coverage, and relevance for that purpose.

Using the listed data sources, three base maps were created utilizing Esri's ArcGIS: (1) a state overview map, (2) a watershed index map, and (3) detailed watershed maps. Together, these maps implemented each of the water allocation decisions themes. Appendix A contains a detailed description of the geoprocessing steps for each layer.

Table 1 Table of Thematic Layers for Water Allocation Use Model

Name	Thematic Description	Geographic Description	Scale	Source
Montana Water Rights	This dataset contains information about water right claims, including beneficial use, appropriation date, and places of use.	This dataset contains a point location representing the centroid of the area where water is diverted from a source and put into use, based on its legal description.	1:100,000	(Montana State Library 2011)
National Hydrography Dataset Plus (NHDPlus)	This dataset contains information about the hydrological regime of the landscape, including surface water features, and direction of flow.	This dataset contains several layers related to surface hydrology, including linear features, an elevation raster grid, and basin area boundaries.	1:100,000	(Horizon Systems Corporation n.d.)
Major Rivers and Water Bodies	This dataset displays labeled major rivers, water bodies, and hydrologic landmarks	This map service contains linear and area features and annotations showing major rivers and water bodies	1:100,000	(U.S. Environmental Protection Agency n.d.)

Table 2 Table of Reference Layers for Water Allocation Model

Name	Reference Description	Geographic Description	Scale	Source
Public Land Survey System	This dataset provides the legal description of where water is diverted and used	This dataset contains a hierarchal series of rectangles, square, and other irregularly shaped area layers that describe the location of a diversion point or place of use to within 1/16th acre.	1:24,000	(U.S. Bureau of Land Management 2011)
Terrain/Shaded Relief	This dataset provides an image of the terrain and relief within the study area landscape, showing locations of peaks, valleys, and other generalized features.	This dataset provides a snapshot of the study area's relief and elevation in a raster format as a basemap.	30-meter (Shaded Relief); up to 1:70,000 (Terrain)	(Esri 2012b)
County Boundaries Major Cities Roads	These layers situate water right claims within the community of water users and infrastructure of the study area.	These point, line and area-based datasets describe major forms of infrastructure on the landscape.	Various	(Montana State Library n.d.)

Each map was exported as a geospatial PDF from ArcMap. This format enables easy distribution and viewing of the map while preserving a limited set of tools that allow the user to interact with the map, such as turning layers on and off and identifying attributes (Esri 2012a).

3.2.2 Basemaps

The state overview map placed the Ruby River drainage basin into the hydrologic context of the Missouri River and the geographic context of Montana. It used an inset technique to provide a small zoomed in overview of the study area next to the large overview map of the state. The watershed index map was designed as an inverse of the state overview map, focusing on the Ruby River drainage basin while retaining a smaller inset map of the state for context. One detail map was created for each major watershed (Upper, Middle, and Lower Ruby River, Alder Gulch Creek, and Sweetwater Creek) in the study area. Each map focused on a particular watershed and displayed places of use associated with surface water right claims within the study area and all landmark features shown on the watershed index map.

3.2.3 Implementing the Water Allocation Themes

The theme 3.1.1 (Upstream Appropriation Affects Downstream Users) was achieved on the state overview map by describing the hydrologic connection between the Ruby River drainage basin and the Missouri River, visually and through narrative text. Symbology and Adobe Reader's interactive visibility tools were used to visualize themes 3.1.2 (Water Rights Reflect the Values of a Place) and 3.1.3 (Water Rights Have a Hierarchy) on the watershed detail maps.

The goals of theme 3.4 (Water Rights are Linked to a Physical Landscape) were achieved on the watershed detail maps. Points of use associated with surface water right claims were visualized within the context of the major social and natural features of the Ruby River drainage basin. By toggling the visibility of various combinations of beneficial use and priority year groups, map users can observe how the distributions and patterns changed with respect to the study area’s communities and landscape. The watershed index map enhanced theme 3.4 by providing an overview of the major physical and social landmarks and features of the Ruby River drainage basin.

Two different methods were tested for symbolizing water right beneficial uses and seniority based on priority year. In the first method, black-and-white pictographic symbols that represented each beneficial use were selected from the ArcGIS Stylesheets (Figure 2). The symbolized layer was then subdivided into twelve sub-layers that represented each decade from 1900 to the present year, 2012, based on each point of use’s year of appropriation. One of those sub-layers contained all points of use dated earlier than the year 1900. A thirteenth sub-layer contained all points that lacked an enforceable priority date and thus were undated. The pictography symbology set was applied to all sub-layers for consistent display. This method allows readers to toggle the visibility of each decade and visualize changes in both seniority and geographic distribution for each beneficial use over time using Adobe Reader’s layer visibility tools. These tools are provided as part of Adobe Reader’s support for the geospatial PDF format and do not require additional plug-ins or use of Adobe Acrobat.

Figure 2 Screenshot of Pictographic Symbol Set for Beneficial Use

The second method was symbolized using uniform small dots to reduce visual clustering and overlap in areas of high density. The points of use layer was then subdivided into thirty-six group layers representing the seven most common beneficial uses in the study area (including an "other" category) and five sub-groupings based on year of appropriation. A sixth sub-group was created for undated points of use.

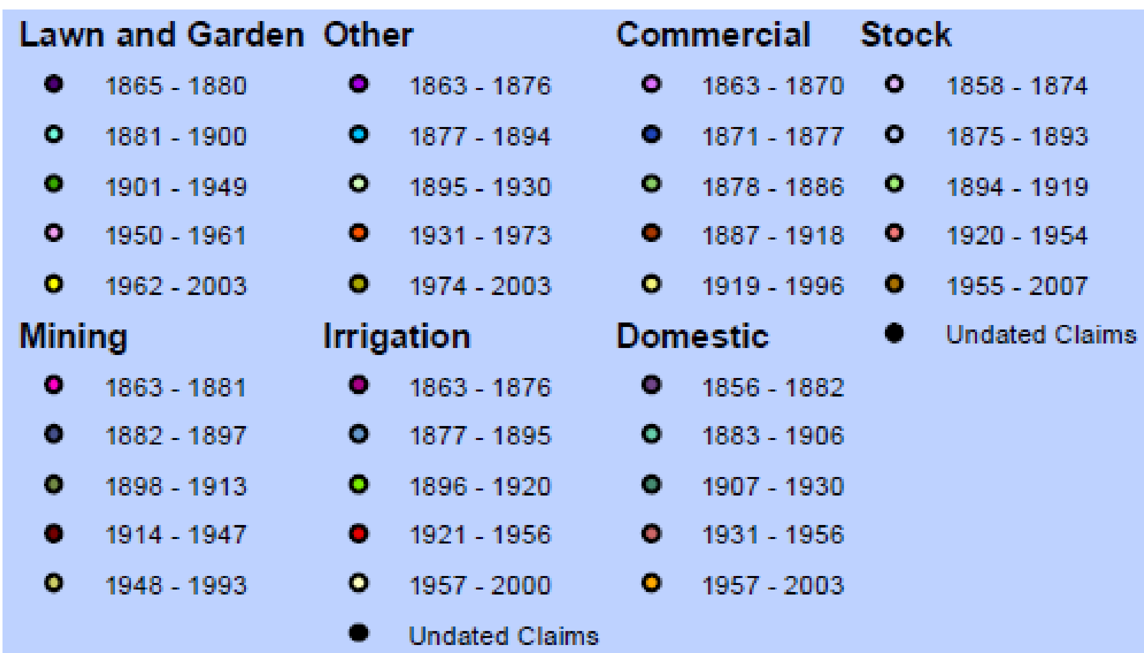


Figure 3 Screenshot of Dot-Based Symbol Set based on Beneficial Use and Year of Appropriation

As shown in Figure 3, the members of the five symbol classes in each group layer were determined by applying a natural breaks (Jenks) classification to each beneficial use group layer's year of appropriation field. The dots in each sub-layer were then assigned one of thirty-six unique colors that varied based on beneficial use and the year of appropriation classification. This allows map users to toggle the visibility of both beneficial uses group layers and priority use sub-layers.

3.2.4 Expert Evaluation

Eleven individuals with a professional interest in the Ruby River drainage basin and its water rights were asked to voluntarily evaluate the maps produced from the model and provide verbal feedback. Six of the eleven individuals were selected based on their membership in organizations known to have an interest in Ruby River drainage basin, specifically the Ruby Watershed Council, the Montana Department of Natural Resources, Project Water Education for Teachers (WET), and Madison County government. The other five individuals were referred by one of the five initial respondents. All were initially contacted by phone to gauge their interest in providing feedback.

If the experts contacted indicated interest or no response was received, they were sent a follow-up email message containing more information about the project and the role of their feedback before making a final decision. Of the eleven individuals contacted, seven expressed interest in reviewing the maps and confirmed their availability (Appendix B). After reviewing the email, interested individuals contacted the author to set up a 1-2 hour phone interview. Interviews occurred between May 4 and 11, 2012.

During the interviews, each individual was asked to visit the website https://join.me and enter a code provided by the author. This code enabled them to view the author's computer screen, upon which each of the maps were displayed using Adobe Reader. Each respondent then provided verbal feedback, which the author transcribed on screen using Microsoft OneNote to ensure accuracy.

3.3 Structure of the Evaluation

The request for feedback on the cartographic portfolio was structured around three categories: (1) the cartographic design, (2) communication of the water allocation decision themes identified above in section 3.1, and (3) interactivity (toggling visibility). The questions posed to each reviewer can be found in Appendix C. Map design principles were used to evaluate cartographic design feedback while several sources were used to evaluate the interactive features of each map.

Robinson et al. (1995) offer several map design principles that can be used to evaluate a map's cartographic design. A map should be *legible*: the fonts and graphic symbols should be large enough to be seen clearly. It must also have *visual contrast*, allowing map users to distinguish between symbols and feature, not only using size, but also using color, texture, and shape, among other examples. Finally, a map must have good *figure-ground* organization. This refers to the map user's ability to differentiate features or layers that are more important (i.e., *figure)*, based on the cartographer's objectives. In addition to these principles, cartographers must be aware of several constraints that affect map design, including its *purpose*, the geographic *reality,* *availability* of spatial data, *map scale*, *audience*, *conditions of use*, and *technical limitations*.

Lobben's (2003) classification of cartographic animations and MachEachren's (1994) paradigm of cartographic visualization, as discussed in Andrienko and Andrienko (1999), can be used to evaluate this study's interactive maps. According to Lobben (2003), the maps falls most closely into the *time-series* class because the map area is held constant, while one or more geographic variables are represented dynamically as they change over time. Lobben (2003) suggests that the temporal rate of change be made as constant as possible (e.g. by decade, not sporadically by one, three, and then two year intervals).

According to Adrienko and Adrienko (1999), interactive maps can support, and even enhance, a map user's ability to "reveal unknowns" about the map data. To do so, interactive maps should promote *interactive exploration of map data*. One method for doing so is providing *multiple representations* of map data that enable map readers to see changes in spatial patterns or distributions. Peterson (1999) adds that map legends should become dynamic access points for interacting with the map. Linking interactive map legends to the display of map content enhances their explanatory power.

CHAPTER 4: RESULTS

This section presents several of the maps created as part of this study. Each map was selected because it illustrates one or more of the themes from section 3.1. Other examples of the maps can be found in Appendices E through J. This section also presents the expert feedback obtained from the individuals contacted for this study.

4.1 Presentation of Interactive Maps

The state overview map shown in Figure 4 achieved the goals of theme 3.1 (Upstream Appropriation Affects Downstream Users). Its accomplishments include presenting the connection between the Ruby River drainage basin and its downstream neighbors graphically and narratively, and displaying the study area at multiple scales. It also serves to introduce an unfamiliar reader to both the state and to the study area. The map consists of three primary components: (1) a large view of the state of Montana, (2) a smaller inset showing the study area and its watersheds, and (3) a narrative text description of the connection between the study area and its downstream neighbors. The large view displays the major rivers of Montana, such as the Clark Fork, Bitterroot, Madison, Milk, Missouri, Sun, and Yellowstone. It also frames the study area and its two counties, emphasizing that the Ruby River flows through it. The smaller inset map zooms in on the study area and displays the major watersheds, Ruby River, county boundaries, and major rivers surrounding it: Big Hole, Beaverhead, and Madison. Using a shade of gray for the county boundaries and strong bold colors for the other features creates a strong visual contrast and visual hierarchy on the state overview map. Transparency and a mixture of light and dark colors achieved the same effect on the study area inset.

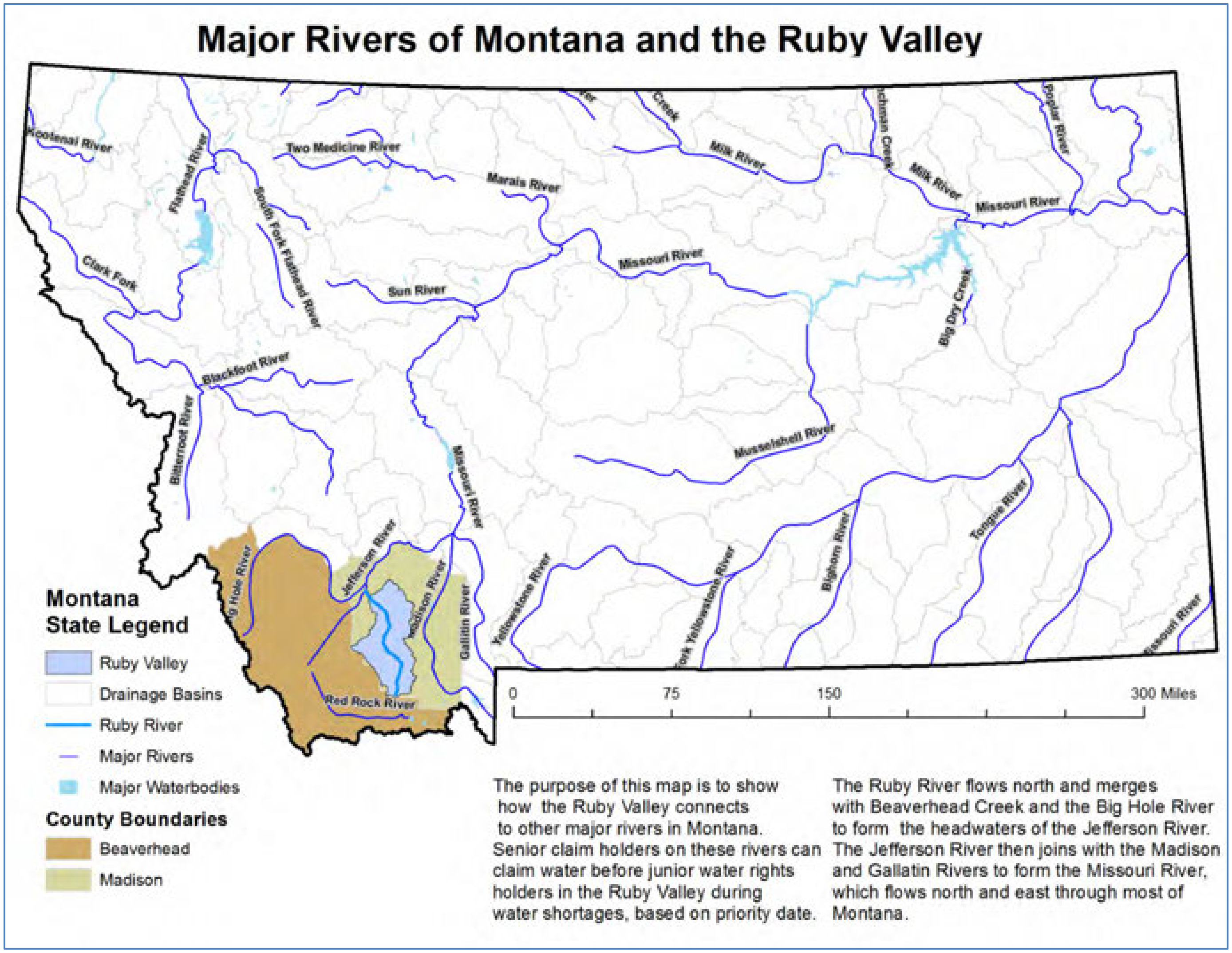


Figure 4 State Overview Map Showing Major Rivers and the Study Area

The watershed index map shown in Figure 5 contributed to the goals of theme 3.4 by introducing the map reader to the major physical and social features, and the physical landscape of the study area that is governed by Montana water right policies and claims. Its major accomplishment is to present a select number of landmarks and major features within the study area to orient the map reader without introducing significant clutter to the map. As with the previous map, the watershed index map consists of three primary components: (1) a large view of the study area, (2) a smaller inset showing the state of Montana, the study area, and major rivers, (3) a narrative text description of the purpose of the map.

The inset displays a smaller view of the state from the previous map, as a reminder of the study area's context. The larger map provides a more detailed view of the study area's social and natural features. Examples include major towns (e.g. Sheridan and Virginia City), watersheds (Upper, Middle, and Lower Ruby River, Sweetwater Creek, and Alder Gulch), and county boundaries. One of the more important additions to this map is the townships, each six miles on a side and thirty-six square miles in area. They are the largest areal unit in the Public Land Survey System used in a legal description of the location of water right claims, both for points of use and for points of diversion. On the map, they serve as a coarse graticule and provide a tangible sense of scale. A shaded relief background provides a sense of the terrain and elevation change within the study area. Transparency and a mixture of light- and dark-colored symbols were used to provide visual contrast and create a visual hierarchy. For example, the Ruby River's bright blue symbol is very distinct from the darker purple watershed boundaries.

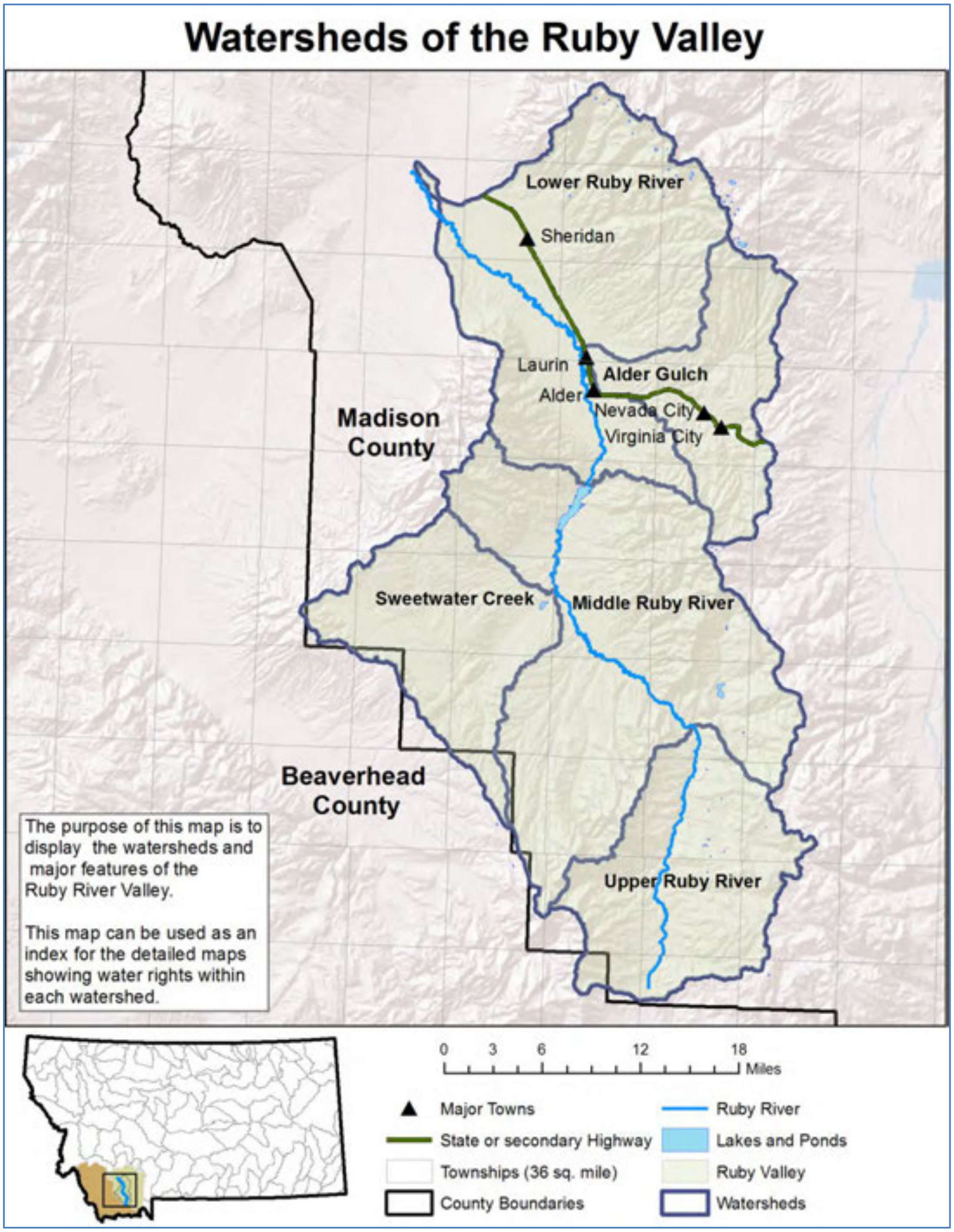


Figure 5 Watershed Index Map of Study Area

The watershed detail map for The Lower Ruby River Watershed is shown in Figure 6 (pictographic symbol set) and Figure 7 (dot-based symbol set). They visualize theme 3.4 (Water Rights are Linked to a Physical Landscape) by relating points of use for water right claims within the context of the physical landscape, natural, and social features. Themes 3.2 (Water Rights Reflect the Values of a Place) and 3.3 (Water Rights Have a Hierarchy) are discussed separately below since they have different presentations on each map. Design components common to Figures 6 and 7 include a large view centered on a single watershed and narrative text that briefly describes the purpose of the map, lists the primary agency and legislation governing Montana water rights and defines the permitted, or beneficial, uses of water. Figure 7 adds a small inset map to the left of the map's title that displays the outline of the highlighted watershed within the drainage basin, continuing the tradition of displaying information at multiple scales.

This map also expands the number of reference and thematic layers used to provide context to the water right points of use layer. In addition to the layers shown on the watershed index map, this map displays the major roads, streams, lakes, ponds, canals, and ditches within the study area. Points of use were shown using both symbols (Figure 6) and dots (Figure 7). Labels were both automatically and manually generated for selected features in an attempt to balance highlighting important landmarks and avoiding overcrowding of the map. The visibility of all layers could also be toggled to limit overcrowding. Bright colors were used to highlight the linear hydrologic features and roads to make them stand out from the darker background fills. A strong maroon color was used to make the highlighted watershed for each map stand out from the others.

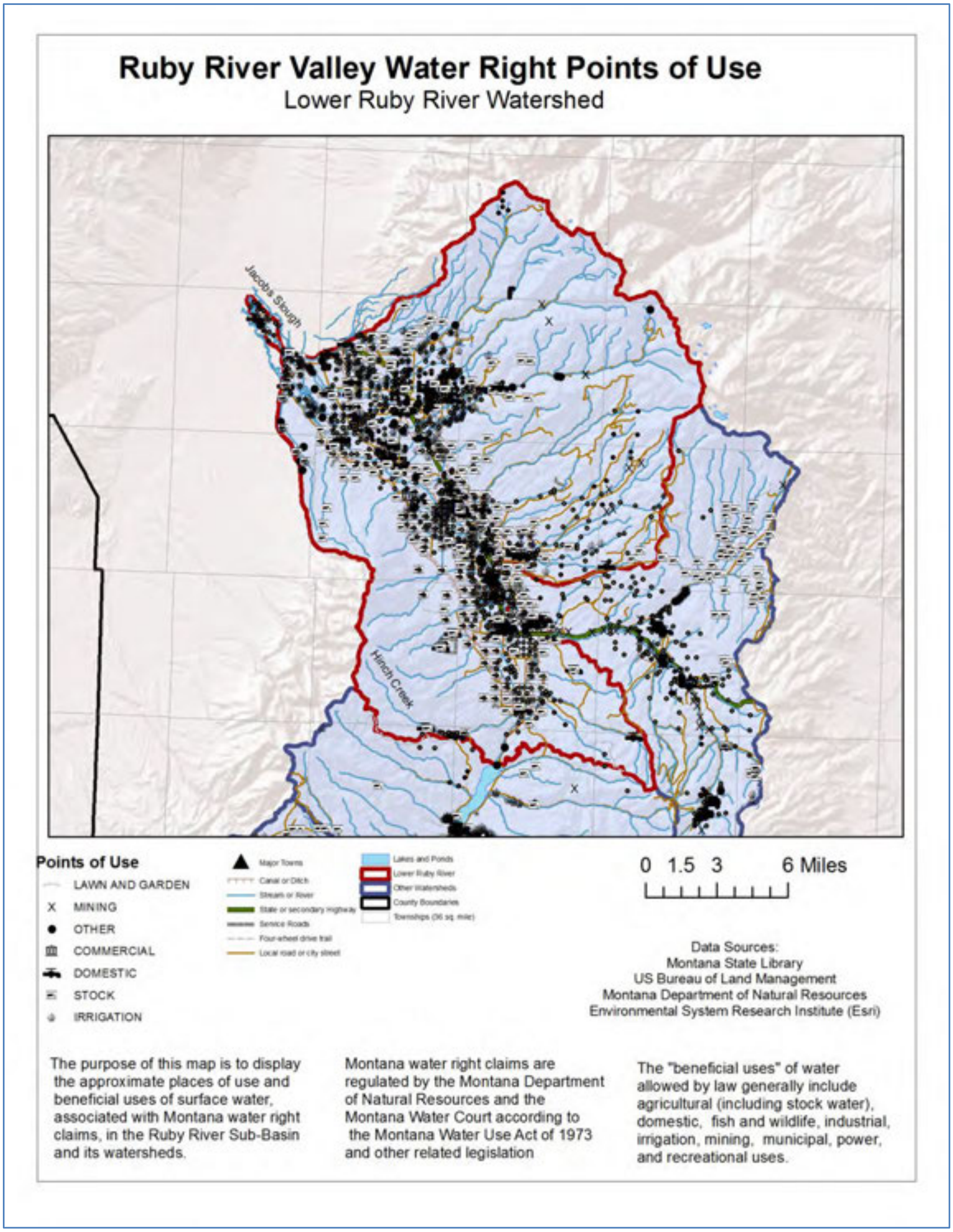
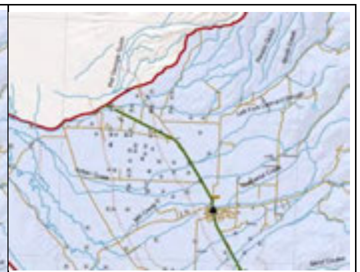
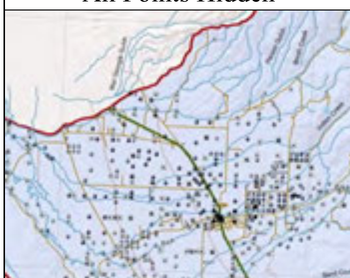
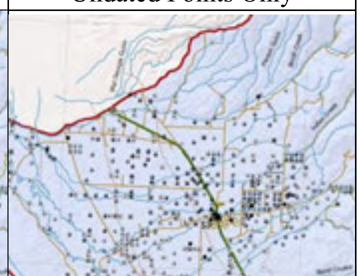
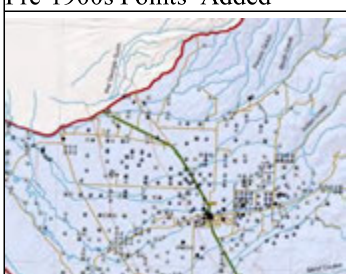
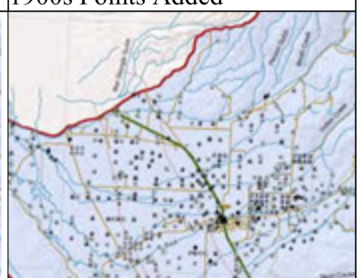


Figure 6 Detail Map for Lower Ruby River Watershed with Pictographic Symbol Set

4.2 Presentation of Interactive Features

Table 3 Time Series Screenshots of Points of Use in the Lower Ruby River Watershed

	
All Points Hidden	Undated Points Only
	
Pre-1900s Points Added	1900s Points Added
	
1910s Points Added	1920s Points added

The first symbol set uses a single set of symbols to represent the beneficial use of each point of use and groups the points by decade according to their priority date. Using the layer visibility tools, one is able to view the historical progression of water right allocation by beneficial use (Table 3). Readers can make observations like, "many claimed points of use were either undated or established before 1900", but may find it difficult to observe or infer the progression of a single beneficial use, e.g. stock due to the size and crowding of symbols.

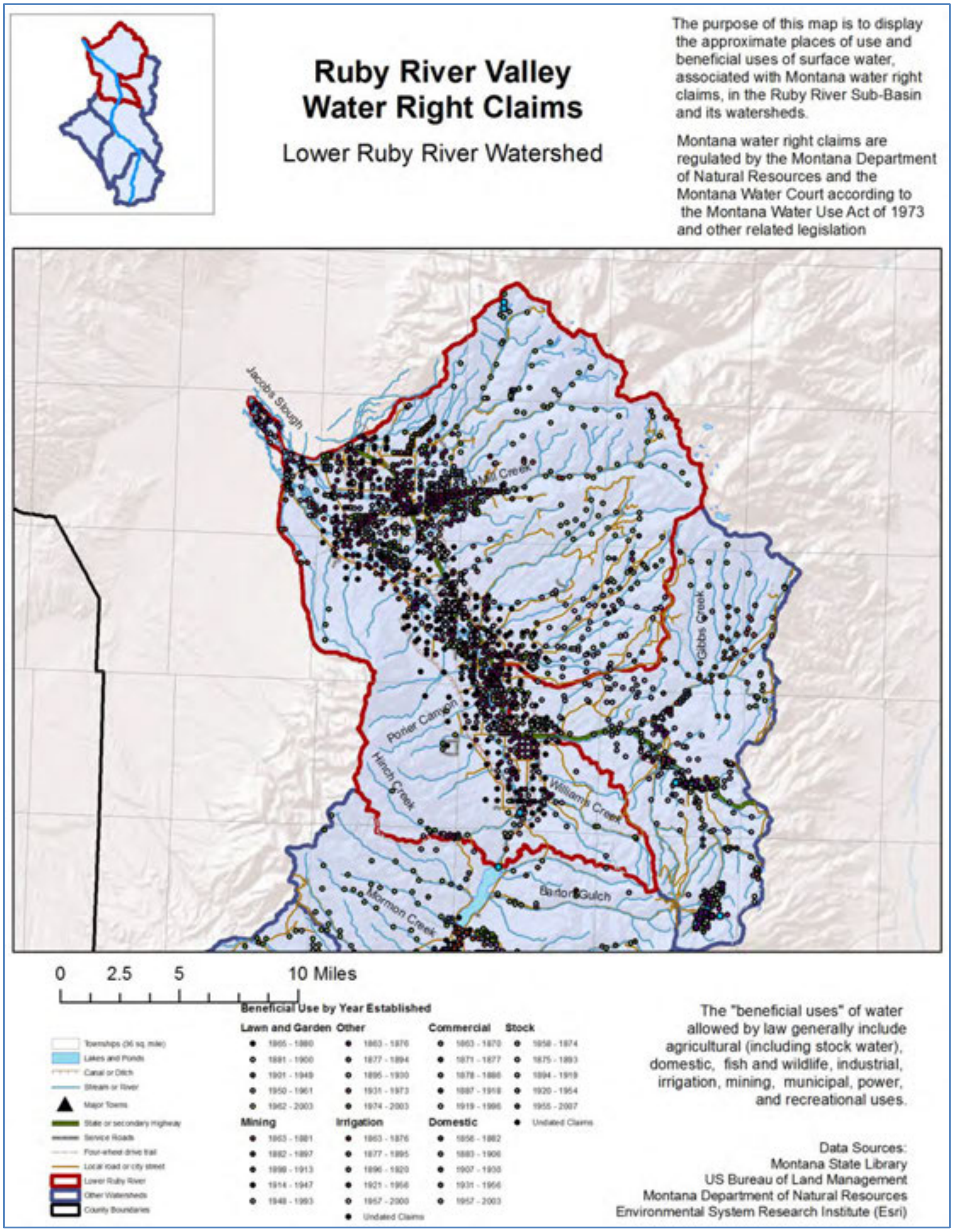
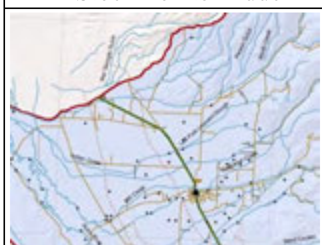
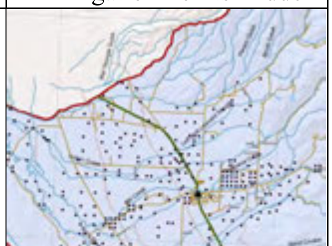
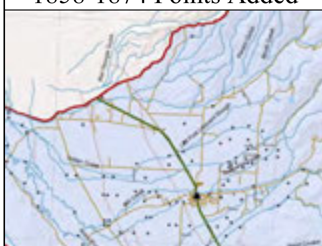
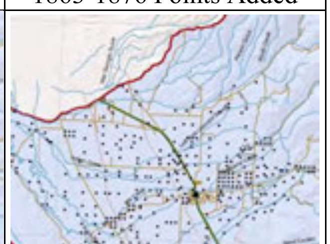
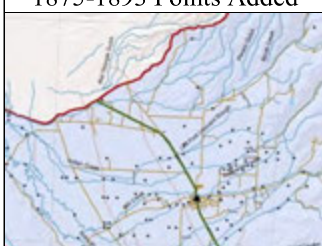
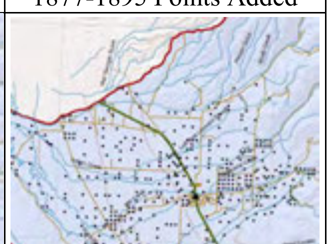


Figure 7 Detail Map for Lower Ruby River Watershed with Dot-Based Symbol Set

Table 4 Time Series of Stock and Irrigation Points of Use in the Lower Ruby River Watershed

	
All Stock Points Hidden	All Irrigation Points Hidden
	
1858-1874 Points Added	1863-1876 Points Added
	
1875-1893 Points Added	1877-1895 Points Added
	
1894-1919 Points Added	1896-1920 Points Added

In contrast, the second symbol set uses dots to represent all points of use and differentiates between both the beneficial use and priority year using color. Compared to the pictographic symbol set, the dot-based symbol set makes it easier for the map reader to observe the progression of points of use over time for a particular beneficial use and compare the progression of two or more beneficial uses. In Table 5, one can observe that for both stock and irrigation, the majority of claims were established between 1850 and 1876 and that some stock points of may be associated with claims that are senior to claims associated with irrigation points of use. Another observation is that irrigation points of use are more clustered than stock points of use.

4.3 Presentation of Expert Feedback

Each map is evaluated below based on expert (local) knowledge according to its cartographic design, communication of water allocation themes, and interactive features, using the feedback obtained in response to the interviewer's questions (Appendix C).

4.3.1 State Overview Map

The purpose of this map (Figure 4) was to place the Ruby River drainage basin into the hydrologic context of the Missouri River and the geographic context of Montana, and communicate the theme 3.1(Upstream Appropriation Affects Downstream Users). Since the map's content was static, the reviewers did not evaluate the interactive features of this map.

Sarchet's (2012) general impression of the map spoke for the other reviewers: "It's a good reference map and puts things in context." Sarchet (2012) also liked the description of the Ruby River's hydrologic connection to the Missouri River: "The text description is helpful to tell the story of the map and its purpose." The map content and design were also critiqued. Kruer (2012) had trouble with some of the map symbology: "[The] inset map colors cause confusion - blue for river is hard to distinguish from blue for watershed boundaries." Fechter (2012), Kruer (2012), and Schwend et al. (2012) jointly identified a mistake in the default label for an area river, noting that "Beaverhead Creek should be labeled Beaverhead River." When asked how the map could be improved, Fechter (2012) offered this suggestion: "Add boundaries for Wyoming; Idaho; Dakotas for [added] emphasis on Bakken [oil field] and Yellowstone National park."

4.3.2 Watershed Index Map

The purpose of this map was to show the watersheds and major social and physical landmarks within the Ruby River drainage basin and communicate theme 3.14 (Water Rights are Linked to a Physical Landscape). Since the map's content was static, the reviewers did not evaluate the interactive features of this map.

Constructive criticism comprised much of the feedback for this map. Many of the comments focused on the color and hierarchy of map symbols, and the map design, as this example shows: "The highway stands out too much if watersheds are the primary theme" (Fechter 2012; Sarchet 2012). Other criticisms focused on how map features were labeled, the presence or absence of important landmarks, and the cartographic symbols used, as illustrated by this quote from Fechter (2012): "Ruby Reservoir needs to be labeled; [it is an] important landmark for people." Gilman (2012) and Schwend et al. (2012) challenged the displayed watershed boundary definitions using the Ruby Reservoir as a reference. In Gilman's (2012) words: "Local residents refer to anything 'above' the Ruby Reservoir as 'upper ruby' and anything 'below' the reservoir as the 'lower ruby'." To improve the map, Fechter (2012) recommended adding local tributaries and Schwend et al. (2012) suggested adding some basic information about the study area, such as its size or population.

4.3.3 Watershed Detail Maps

The purpose of these maps was to show the points of use associated with Montana surface water right claims in the study area, their permitted use, and seniority, within the context of the others layers listed in Tables 1 and 2, some of which were visualized on the previous maps.

Additionally, the maps were intended to communicate themes 3.1.2 (Water Rights Reflect the Values of a Place), 3.1.3 (Water Rights Have a Hierarchy), and 3.1.4 (Water Rights are Linked to a Physical Landscape).

The reviewers were highly engaged by interacting with the maps and observing changes in the geographic distribution of points of use (and their beneficial use) over time. Sarchet (2012) was enthusiastic about the layer visibility tools built in to Adobe Reader: "There is a lot of information on these maps, but the ability to turn on/off them off makes it [the maps] flexible enough." Both Kruer (2012) and Gilman (2012) identified the approximate locations of their water right claims and points of use. Most of the reviewers knew that mining was a common beneficial use of water rights in the Alder Gulch watershed, but Kruer (2012) was surprised by the density of irrigation points of use in the Lower Ruby River watershed.

Unfortunately, the detail maps suffered from many cartographic flaws affecting the other maps since they shared the same data sources and symbology sets. Reviewers also critiqued the natural breaks (Jenks) classification used to derive the colors for the dot-based symbol set. This was a problem unique to the detail maps. As Sarchet (2012) put it: "The dot colors are difficult to tie to the legend. The variety of colors and years make it difficult to remember what's on the legend when looking at the maps."

Simply visualizing the points of use associated with Montana surface water right claims revealed certain limitations and errors with the water rights source data that were not always known to the reviewers.

For example, the precision of the legal description used to locate points of use varies markedly between different points of use. This can result in several points of use being stacked at the same location, since the DNRC places each point at the geographic center of the area covered by the legal description, such as a section (Montana State Library 2011). This problem was only apparent with the use of a GIS, but was explained to reviewers during each interview.

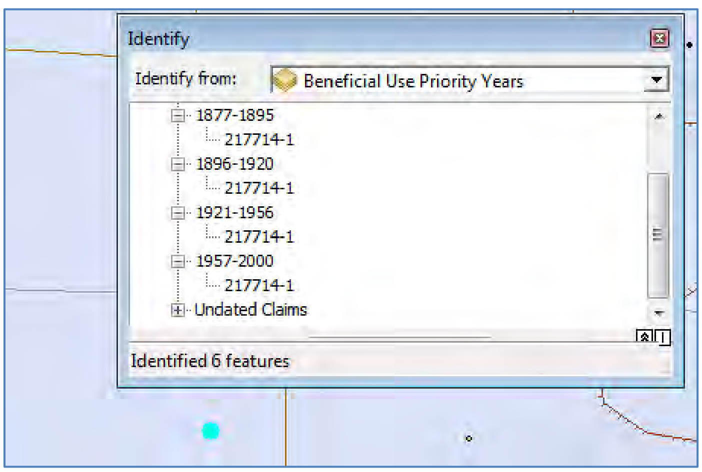


Figure 8 Screenshot of Points of Use exhibiting "grid effect"

In Figure 8, six points of use are stacked at the same location, shown by the highlighted blue circle. A related effect is that the points assume a regular grid pattern when they are ascribed only to a township, range, and section. Each point is placed at the center of the section. This effect was clearly visible in the Upper Ruby River watershed (Figure 9). Kruer (2012) was frustrated with the inaccuracy of the points of use data: "[His] big wish was correcting accuracy of water right locations...the current data is not useful." Schwend et al. (2012) also noted that the current grouping of "other" beneficial uses lumped in fly-fishing, one of the "three main industries" in the Ruby Valley, with other less important beneficial uses.

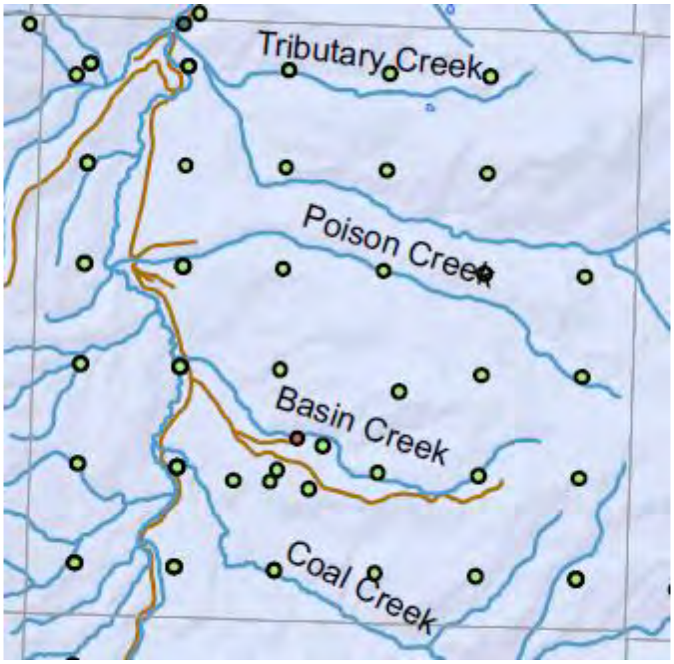


Figure 9 Screenshot of Points of Use exhibiting "stacking effect"

As with previous maps, the reviewers had a solution for every critique they offered. Schwend et al. (2012) recommended displaying fly-fishing as a separate beneficial use category and offered an alternative to the natural breaks (Jenks) classification: "Simplify water right priorities to useful classes and tie them to history - e.g. 1910 homestead act, 1973 water use act". Gilman (2012) agreed with the second suggestion and offered a small vignette to illustrate a real-world example of this approach:

> The 1910 homestead act patents were often used as a proof for 1900s era water rights to show when irrigation ditches were dug and water was claimed...When [the] 1973 water use act was established...this was the method used in order to grandfather in an older water right.

Despite their imperfect design, it was clear the reviewers thought the maps had great potential for communicating their intended water right themes to stakeholders. Sarchet (2012) thought the maps could be useful for illustrating themes as part of a presentation, perhaps "showing locations/distribution of water use by beneficial use types."

Kruer (2012) found a potential advantage to the errors and inaccuracies in the study's visualization of water right data. By making users aware of such errors, *"m*aps can be used to increase the equity and fairness of the water rights system" (Kruer 2012).

To further improve the maps, several reviewers suggested adding content to make the maps even more informative. Kruer (2012) suggested adding points of diversion as an additional layer. Gilman (2012) affirmed this suggestion, saying it might highlight "the 'up the ditch right'." As he explained: "Sometimes junior right holders who are upstream of a senior right holder get first preference. It's not legal, but [it] sometimes happens anyway." Schwend et al. (2012) also expressed interest in adding groundwater rights to the map: "Showing the relationship between surface water and groundwater rights would be very useful for water users and planners."

CHAPTER 5: DISCUSSION AND CONCLUSION

This study aims to improve stakeholder understanding of the policy and science that drive water allocation decisions. Following Maceachren and Brewer‘s (2004) framework of GIS roles in group decisions, the study hypothesized that visualizing components of water allocation would support a stakeholder’s ability to *refine or create knowledge* of water right policies in Montana. To test the hypothesis, a portfolio of interactive maps that visualized beneficial uses and prior appropriation was created and shared with a group of individuals familiar with Montana water rights. This section discusses the study’s results in the context of the hypothesis and supporting literature.

5.1 Can Maps Communicate Water Right Policies?

The goal of this study was to determine whether interactive maps were an appropriate method for communicating water right policies. Wood and Fels (1992) believe that the power of maps is in their ability to connect abstract things such as water right policies with physical landscapes and communities. Ramsey (2009), Couclelis and Monmonier (1995), and Elwood (2006) believe that GIS has the power to visualize decision results and the deliberation process through maps. Adrienko and Adrienko (1999) state that interactive maps can support a user’s ability to “reveal unknowns” about a map by promoting interactive exploration of its data. One method for doing so is providing multiple representations of map data that enable map readers to see changes in spatial patterns or distributions.

Following these authors, this study built a theoretical framework that described: (1) existing social and administrative structures for managing water rights (Yates 1982;

Molle 2004); (2) social value of water that water users might embed in their community culture (Pradhan and Meinzen-Dick 2001); (3) the physical structure of the landscape with which water resources and users interact (Cosens 2009).

This study then applied this framework to a study area, formulating four spatial themes that illustrate how beneficial use and prior appropriation policies are connected to the physical landscape of the Ruby River drainage basin in Montana. The map portfolio provided multiple representations of water rights policies, via these themes, and their connection to the study area's landscape.

The maps also demonstrated the advantages and disadvantages of prescriptive and negotiated approaches to cartography and stakeholder participation. The maps were developed based on knowledge of cartographic design principles, water rights, and the study area, reflecting the tenets of the prescriptive approach, according to Yates (1982). Some of those decisions were incorrect due to incomplete knowledge of the study area. Following a pluralistic approach to creating the maps might have incorporated local knowledge of important landmarks and improved the initial quality of the maps. The process used to solicit feedback for this study achieved many of that approach's goals by allowing stakeholders to interact with and review the maps. Although the feedback generally indicates that the maps have the potential to enhance communication of water right policies to stakeholders, some themes and cartographic techniques were successful while others needed improvement.

5.1.1 Assessment of the State Overview Map

The state overview map's success lay in its simplicity. Its purpose was straightfoward: to introduce unfamiliar readers to the basic geography of Montana, display the study area at multiple scales, and remind readers that upstream actions have downstream consequences. Often, stakeholders are so concerned with the impact of local allocation decisions that they forget that water shortages and equitable water allocation are national, even global, problems. Yet current events remind us that these problems are real and that local actions have consequences at smaller scales than the local geography (Hollenhorst 2012; Nagourney and Barringer 2012).

In this respect, the map succeeded in visualizing the study area and its connection to the Missouri River. Sarchet (2012), in particular, appreciated the narrative description of the Ruby River's connection to the Missouri River as a companion to the map representation. Unfortunately, its achievement was dampened by a lack of visual contrast, confusion of map themes within the main frame, and illegible fonts in the smaller frame.

5.1.2 Assessment of the Watershed Index Map

The watershed index map's goal was more complex than the previous map. This map was designed to introduce the reader to the study area's watersheds, highlight important physical and social landmarks, and act as an index for watershed detail maps. In service of this goal, the map consisted of a large frame containing the study area, its watersheds, and several layers representing social and physical landmarks: major towns, major roads, lakes and ponds, the Ruby River, townships, and county boundaries. A smaller inset frame of the state served as a reminder of the study area's larger context.

This map successfully demonstrated contrasts between the prescriptive and pluralistic approaches to cartography and water right policy development. A pluralistic approach might have obtained local knowledge of landmarks prior to or during map development rather than presenting "finished" maps for feedback as the prescriptive approach did. Regardless of approach, this study underscores Priscolli's (2004) argument that stakeholder participation is critical to ensure that water rights systems account for local conditions. The Geographic Names Information System (GNIS), used to populate the names of hydrography features in the National Hydrography Dataset, takes such an approach. The GNIS support the U.S. Board of Geographic Names, which determines feature names used on federal cartographic products (U.S. Geological Survey 2011).

Local, state, and federal government agencies submit proposed feature names to the Geographic Names Office, which reviews the proposals and enters them into the GNIS if approved. Molle (2004) notes that such pluralistic efforts require a greater investment of time and money and GNIS bears this out: its database is still incomplete despite having collected data for over twenty-five years (U.S. Geological Survey 2011).

5.1.3 Assessment of Watershed Detail Maps

The watershed detail maps had the most complex goal within the portfolio. These maps were designed to visualize water right points of use, their beneficial use, and seniority. In addition, they were intended to show how the geographic distributions and patterns of these attributes change over time. The final goal was to show how the water right policies of beneficial use and prior appropriation were connected to the communities of water users and the physical landscapes within the study area.

To achieve these goals, these maps were constructed with several design features. A large frame focused on an individual watershed, and a small inset frame displayed the watershed's location within the study area. The large frame contained the points of use symbolized according to one of two symbol sets discussed previously and several supporting reference layers: lakes, streams, irrigation ditches, major towns, roads, watersheds, and county boundaries. Narrative text supported the maps by briefly describing their purpose, significant Montana water right legislation, and permitted beneficial uses. Finally, interactive layer visibility tools available within Adobe Reader enabled map readers to interact with the map and explore multiple views of the data.

Cartographically, the maps met with only mixed success in communicating the water policy themes to the map readers. The pictographic symbol set successfully communicated the beneficial use of water rights but failed to account for the high density in some watersheds (e.g. the Lower Ruby River), and reviewers were overwhelmed. The dot-based symbol set handled point of use density more adeptly and made an admirable attempt to visualize the seniority of each point simultaneously. Unfortunately, too many classes of seniority were used to symbolize the points of use, resulting in a color scheme that was too complex and left the reviewers confused and unable to clearly identify either the beneficial use or seniority of a point of use without frequent use of the map legend.

Nevertheless, the layer visibility tools in Adobe Reader overcame many of the maps' cartographic limitations and supported the successful communication of the water right policy themes, particularly when using the dot-based symbology set.

The tools allowed reviewers to simulate time-series animations of beneficial use and seniority, revealed patterns not apparent with static representations of these themes, and highlighted several problems with the current water rights system. For example, imprecise or erroneous legal descriptions are a large factor in the dense clusters of points of use in the Lower and Middle Ruby River and the grid effect visible in the Alder Gulch watersheds. Many of these errors are associated with pre-1973 water rights claims that were established simply by putting water to beneficial use, with no paperwork required. The state is actively adjudicating all pre-1973 rights to determine water availability with greater accuracy and better defend these claims (Legislative Environmental Quality Council 2009). During this process, the state could use a GIS-based data collection method like Mapping Evapotranspiration at High Resolution and with Internalized Calibration (METRIC) (Morse, et al. 1990). It could also increase stakeholder participation to increase the accuracy and precision of its legal descriptions, as an answer to the frustration of users like Kruer (2012) , who expected better representations of points of use on this study’s maps.

5.2 Directions for Future Study

This study was designed to determine whether interactive maps could be an appropriate method for communicating water right policies and support a stakeholder's ability to create or refine knowledge about water rights systems. The results of the study strongly suggested that the cartographic portfolio succeeded in achieving these goals.

Moreover, the feedback confirmed Dix and Ellis' (1998) and Andrienko and Andrienko's (1999) assertion that interaction adds value to static representations by promoting exploration of data and providing multiple representations from which the user may choose. Even so, it is clear that the cartographic quality of the maps needs to be improved to enhance the clarity and effectiveness of the map purposes. Future scholars are encouraged to use the reviewer's suggestions to guide development of better cartographic methods for representing beneficial use and seniority of water right points of use. Cartographers are also encouraged to explore the potential value of Peterson's (1999) active legends in these maps and advanced geospatial PDF features as described in Cervantes (2009).

Further suggestions from the reviewers include adding points of diversion (Kruer 2012) and both points of use and diversion for groundwater water rights to make the maps more comprehensive in scope (Schwend et al. 2012). Points of diversion are just as important for determining seniority of water right claims and highlighting inequities in water rights systems. One example is the "up the ditch right," where a junior water claim is located upstream of a senior water right claim, yet receives greater priority (Gilman 2012).

It is also increasingly clear from the literature that groundwater rights are integral to determining the impact of water shortages on surface water rights and total water availability (Clark Fork River Basin Task Force 2008; Shively and Mueller 2010). Consequently, GIS-based tools used in water rights systems and for maps communicating water right policies should recognize their importance.

This study also established a new direction and role for GIS within water resource management, as many existing GIS applications act in a *decision-support* role (MacEachren and Brewer 2004). Examples include the Texas decision-support system (Wurbs 2005), water quality models (Rosenthal, et al. 1995; Sheng and Wilson 2009) and data collection methods (Allen et al. 2005; Morse, et al. 1990).

The feedback from the reviewers generated several hypotheses related to maps and public participation that further researcher should test. First, Kruer (2012) suggested that the ability to explore and interact with the spatial data using the interactive maps inadvertently increased the transparency of the water rights system used in Montana by communicating the errors and imprecision of water right claim records to stakeholders. Second, maps overcame the limitations of the prescriptive approach used to develop the Montana water rights system and encouraged stakeholder participation through their interactions with the maps during the review process. Third, the element of interactivity transformed these maps from static representations of water rights systems to prototype spatial understanding systems, following Couclelis and Monmonier (1995).

A pre-test/post-test design is commonly used to test whether knowledge has increased in order to control for effects of the cartographic design, user perceptions, or interactions with the maps. Examples of these tests abound in the literature (Jankowski and Nyerges 2001; Jankowski 2009; MacEachren 2000). Researchers are encouraged to verify claims for interactive maps in the water rights domain using these methods.

A final suggestion is to extend the design and application of interactive maps to other areas of the United States with similar characteristics. This may include most of the western states (e.g. Colorado), which use beneficial use policies to regulate how water is used and the *prior appropriation doctrine* to prioritize water right claims during water shortages. However, researchers should take care to incorporate local feedback early on to ensure that these future maps are designed well and recognize the landmarks and community values that are important to local residents. Researchers should also be aware that the structure and content of water right GIS data for other states may vary significantly from the datasets used in this study and make appropriate adjustments.

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APPENDIX A: GEOPROCESSING STEPS

This appendix describes the steps used to prepare the spatial layers used in the interactive maps produced for this study (see Section 3.2, Tables 1 and 2).

Downloading the Data

The ESRI shaded relief basemap and the major rivers and streams map service were added to ArcMap using the appropriate functions. The Public Land Survey System dataset for Montana was downloaded from the Bureau of Land Management's download website (2009). The hydrographic layers were downloaded from the Montana Digital Atlas (Natural Resource Information System, Montana State Library n.d.), which automatically clipped the datasets to the study area. The county boundary layer was downloaded directly from the Montana GIS Portal (http://gisportal.mt.gov) in a geodatabase containing all Montana counties.

Geoprocessing the Data

A geodatabase was created to store and manage the shapefiles downloaded from the Montana State Library and U.S. Bureau of Land Management. The geodatabase's structure (Figure 9) was designed to keep each source dataset in its original spatial reference and organize them by theme. The major rivers map service, shaded relief basemap, counties, roads, streams, lakes, watershed, and major town layers were not geoprocessed.

The **Select by Location** and **Select Feature** tools were used to clip the townships and sections layers to the study area.

Points of use associated with surface water rights were selected with the **Select By Attribute** tool using the WRTYPE field and the following values: "exempt right, irrigation district, provisional permit, statement of claim, stockwater permit."

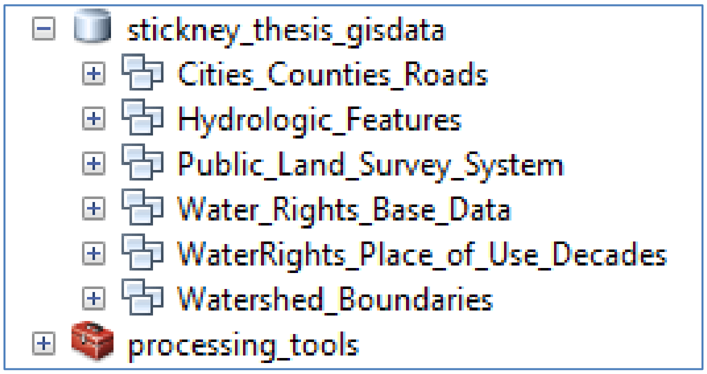
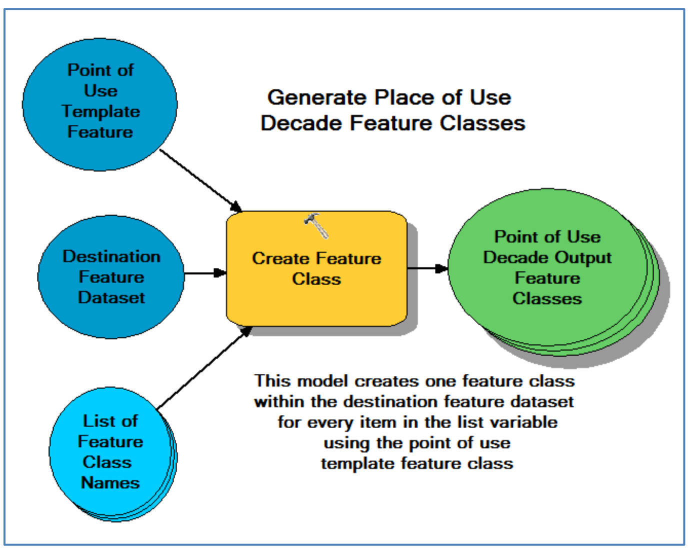


Figure 10 Screenshot of Thesis Geodatabase Structure



Feature classes to hold the points of use in each decade were created using a model (Figure 10). A new field was added to the surface water right points of use layer to hold the priority year of each point, which was extracted from the priority date field using the **Field Calculator** tool. Points of use were selected and added to the feature classes using the **Select by Attribute,** priority year field, and **Append** tools. The pictographic symbol set was applied to these feature classes to create the first series of watershed detail maps. To create the dot-based symbol set, the original surface water right points of use layer was duplicated to create a layer for each beneficial use.

Each of those layers was duplicated five more times for each class in the natural breaks (Jenks) classification, and group layers were created to organize the sub-layers by beneficial use. A sixth layer was added to hold undated claims when needed. Definition queries were used to ensure that the correct beneficial uses were shown in each layer. Most colors were selected from the default palette provided by, Esri while a few were created using the RGB color system.

APPENDIX B: LIST OF INDIVIDUALS PROVIDING EXPERT FEEDBACK

Table 5 List of Individuals Providing Feedback

Name	Occupation	Professional Interest
C. Fecter	Planning Director Madison County	• Trained as a geographer • Has held several jobs related to water rights in Alaska, Nevada, and New Mexico • Currently determines water availability and quality during subdivision reviews
A. Fiaschetti	Hydrologist Montana Department of Natural Resources	• Works in the Water Management Bureau • Serves as a liaison between water users and decision-makers • Assists in developing Montana Water Plan
L. Gilman	5^{th} generation rancher and ranch manager;	• Rancher on family ranch held for 102 years • Manages ranches for absentee owners around Montana • Owns senior water rights with priority date of ~1865
C. Kruer	Wildlife Biologist/Conservationist	• Holds senior water rights on Wisconsin Creek in Ruby River drainage basin • Advocates for water conservation and transparency in water rights
J. Robinson	Planner Montana Department of Natural Resources	• Works in the Water Management Bureau • Serves as a liaison between water users and decision-makers • Assists in developing Montana Water Plan
A. Sarchet	Extension Agent Montana State University Extension Service	• Serves Madison and Jefferson counties • Primary responsibilities are 4-H and agriculture • Gets 4-5 questions per year about water rights or irrigation
A. Schwend	Planner Montana Department of Natural Resources	• Works in the Water Management Bureau • Serves as a liaison between water users and decision-makers • Assists in developing Montana Water Plan • Previous Watershed Coordinator for the Ruby Watershed Council

APPENDIX C: LIST OF QUESTIONS FOR FEEDBACK INTERVIEWS

This appendix contains a list of the questions used to obtain feedback from expert reviewers on the cartographic portfolio created for this study.

Introductory Questions

1. Do you have any questions about this study that were not answered by the email I sent to you previously?
2. Could you tell me a little bit about your current position and your interest in the Ruby Valley and water rights?

General Questions for all Maps

3. Do you have any feedback on the map's design?
4. Do you have any feedback on the map's contents?
5. Does this map communicate its purpose well?
6. Do you think that anything could be added to this map to improve it?
7. Do you think that anything could be removed from this map to improve it?

Specific Questions for Watershed Detail Maps

8. Do you think the interactive layer visibility tools are useful?
9. Do these maps communicate the three water right themes?

Closing Question

10. Do you have any general comments on these maps or other feedback that I may have missed earlier?

APPENDIX D: A NOTE ON THE CARTOGRAPHIC PORTFOLIO

The maps presented in the following appendices and the body of this text have been altered from the original versions presented to the reviewers. The alterations were made both to improve the quality of the maps and to present the interactive maps in a static format for print publication. In appendices E-I, each map series displays the thematic layers individually to simulate the layer visibility tools available with the digital maps.

The following changes were made to each map:

- Remove the publication date and author from each map
- Remove the data sources for each map. The original text displayed was:

  Data Sources:
  Montana State Library
  US Bureau of Land Management
  Montana Department of Natural Resources
  Environmental System Research Institute (Esri)

- Remove three paragraphs of explanatory text from the watershed detail maps

  The purpose of this map is to display the approximate places of use and beneficial uses of surface water, associated with Montana water right claims, in the Ruby River Sub-Basin and its watersheds.

  Montana water right claims are regulated by the Montana Department of Natural Resources and the Montana Water Court according to the Montana Water Use Act of 1973 and other related legislation

  The "beneficial uses" of water allowed by law generally include agricultural (including stock water), domestic, fish and wildlife, industrial, irrigation, mining, municipal, power, and recreational uses.

- Removed the blue background color from the page
- Rearranged map components to achieve the following benefits:
  - Minimize wasted space
  - Maximize map size
  - Increase font size for legibility
  - Increase screen and print resolution
  - Change color of drainage basin on detail maps for contrast

APPENDIX E: MAP SERIES OF BENEFICIAL USES IN UPPER RUBY RIVER WATERSHED

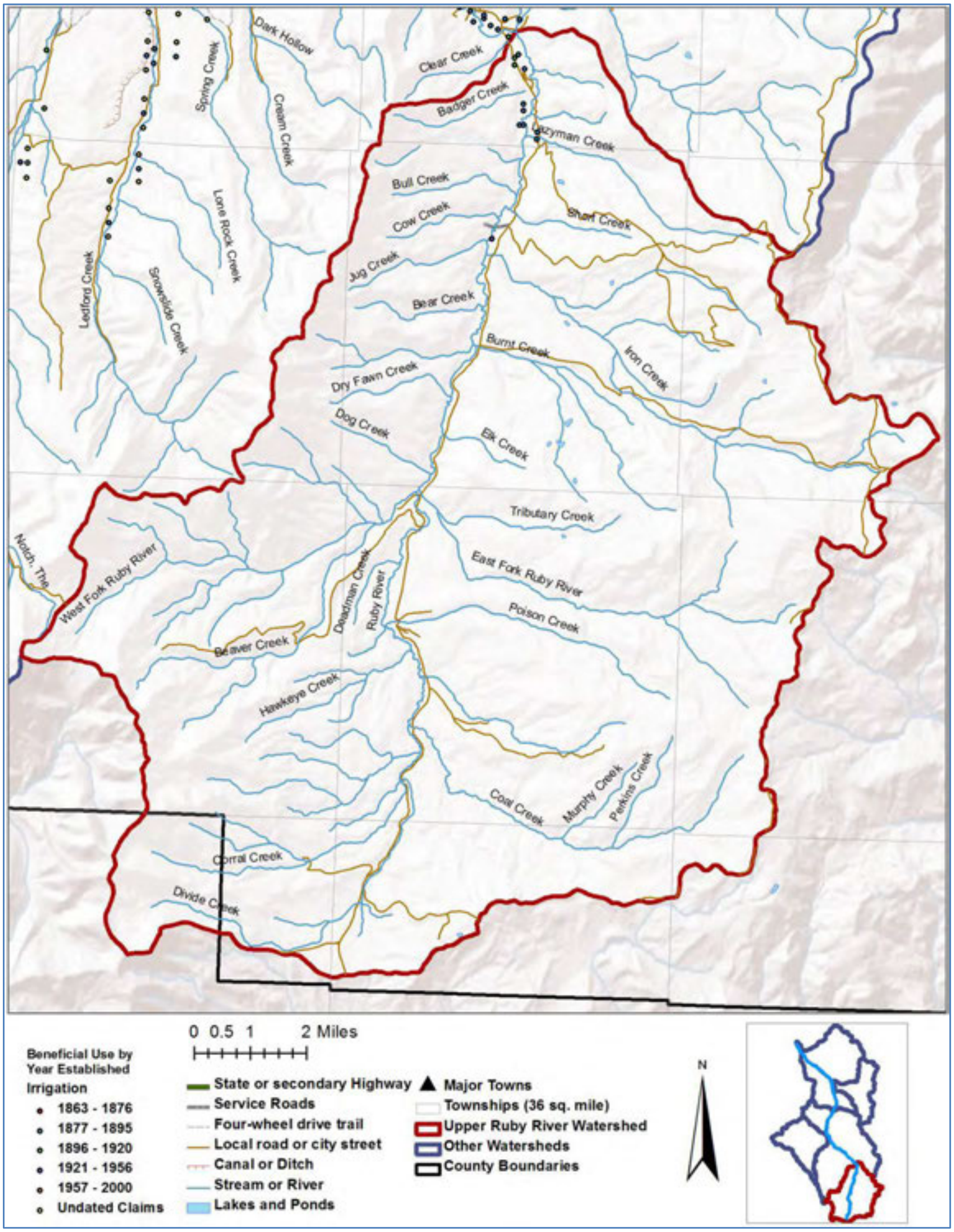


Figure 11 Detail Map of Upper Ruby River Watershed showing Irrigation Points of Use

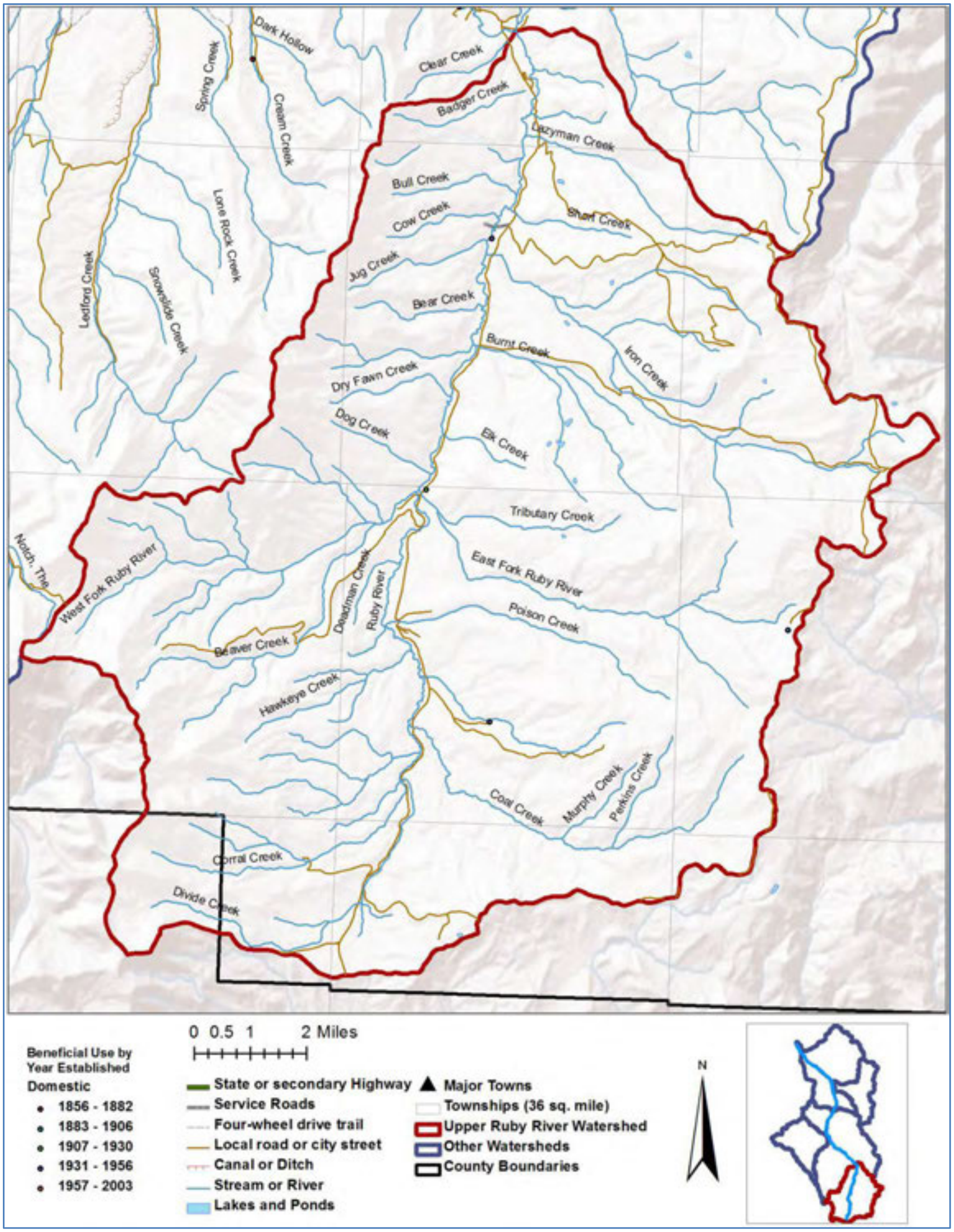


Figure 12 Detail Map of Upper Ruby River Watershed showing Domestic Points of Use

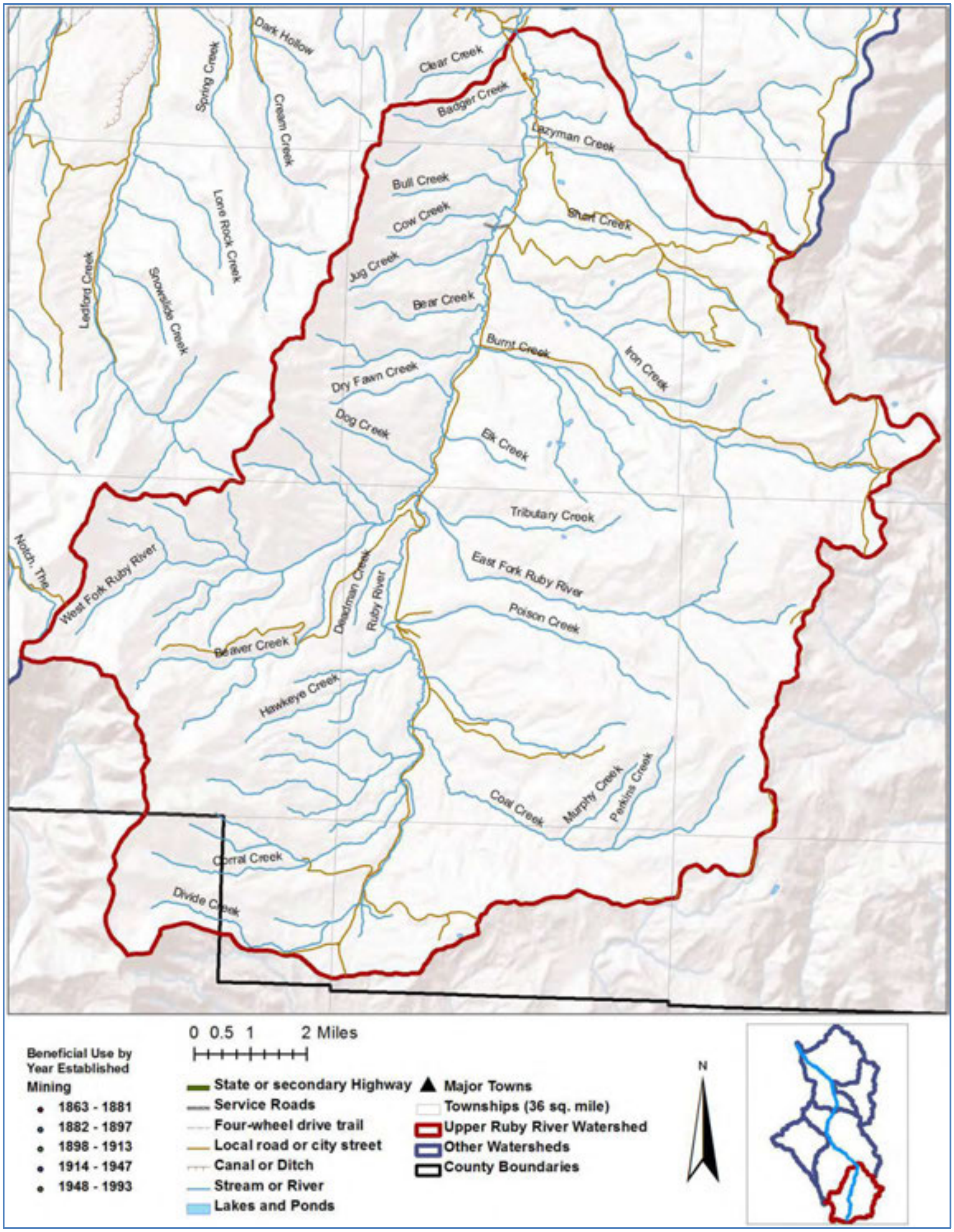


Figure 13 Detail Map of Upper Ruby River Watershed showing Mining Points of Use

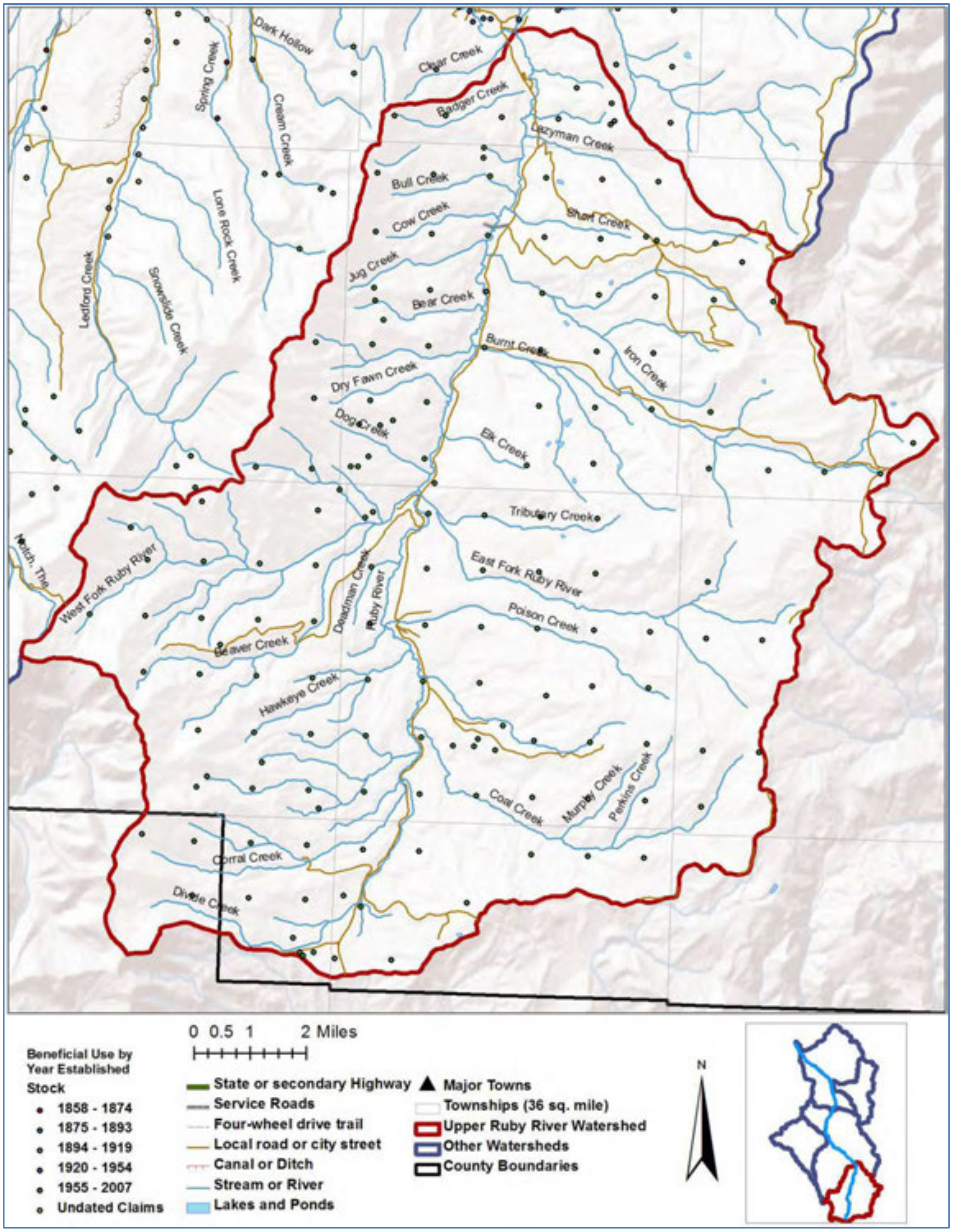


Figure 14 Detail Map of Upper Ruby River Watershed showing Stock Points of Use

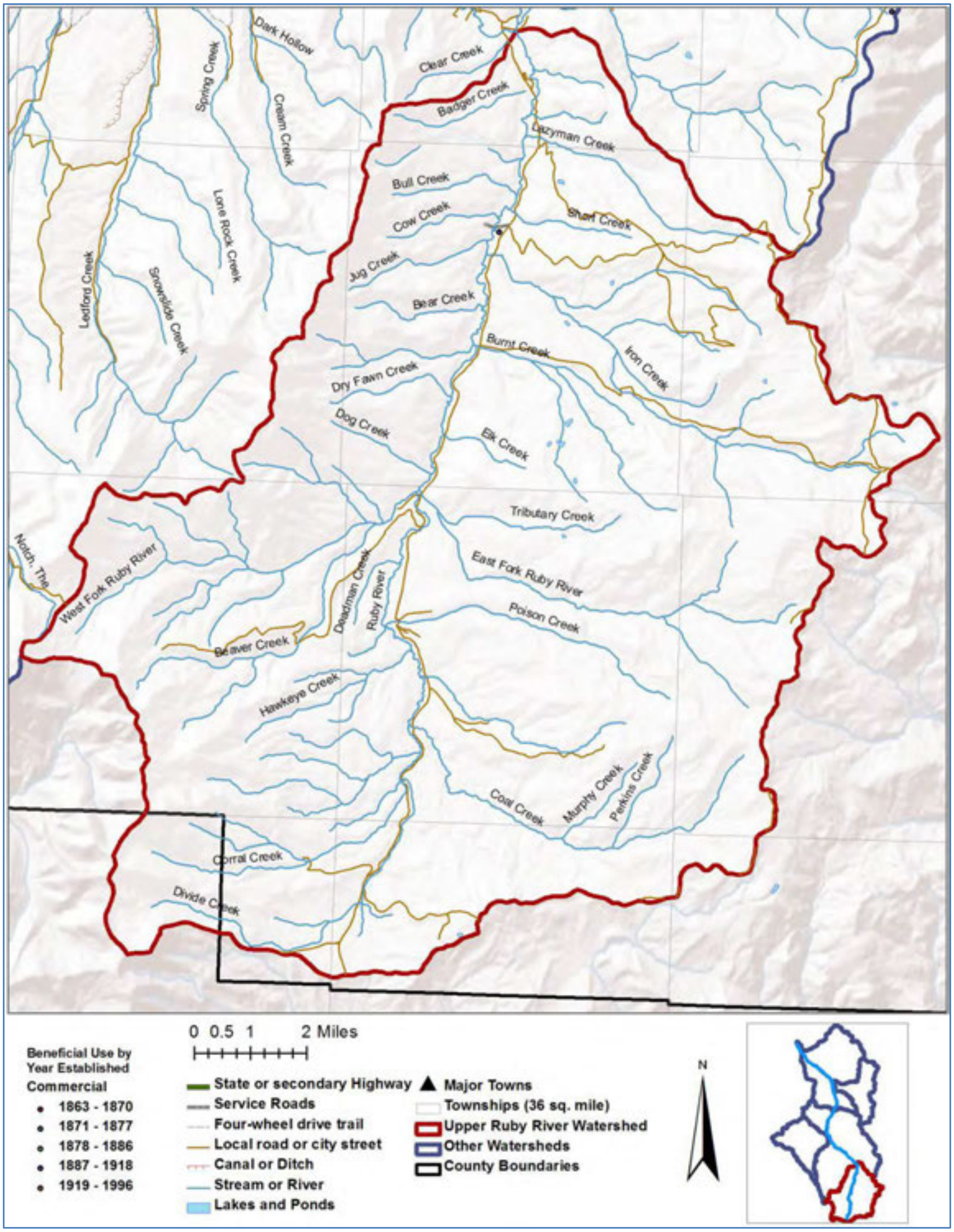


Figure 15 Detail Map of Upper Ruby River Watershed showing Commercial Points of Use

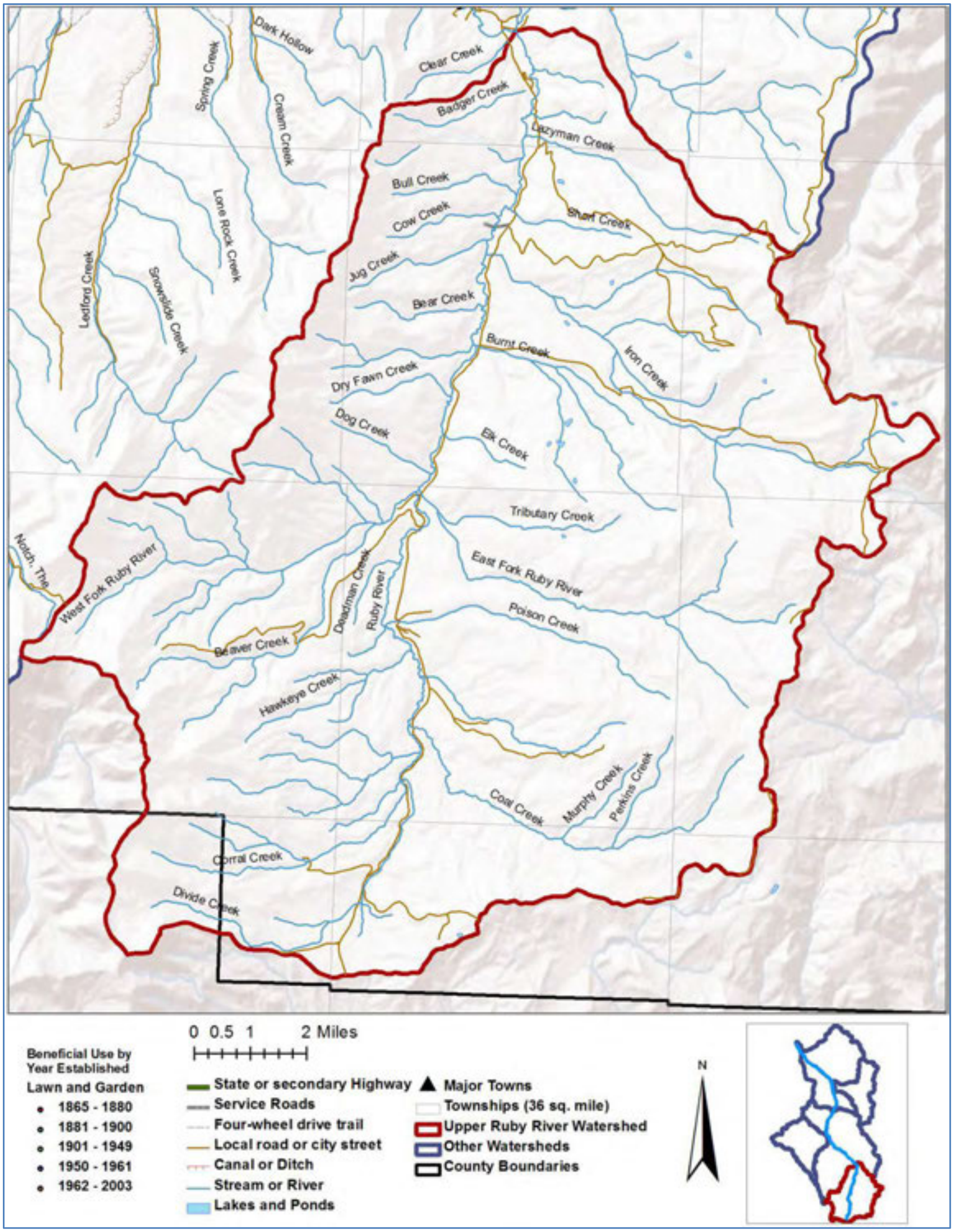


Figure 16 Detail Map of Upper Ruby River Watershed showing Lawn and Garden Points of Use

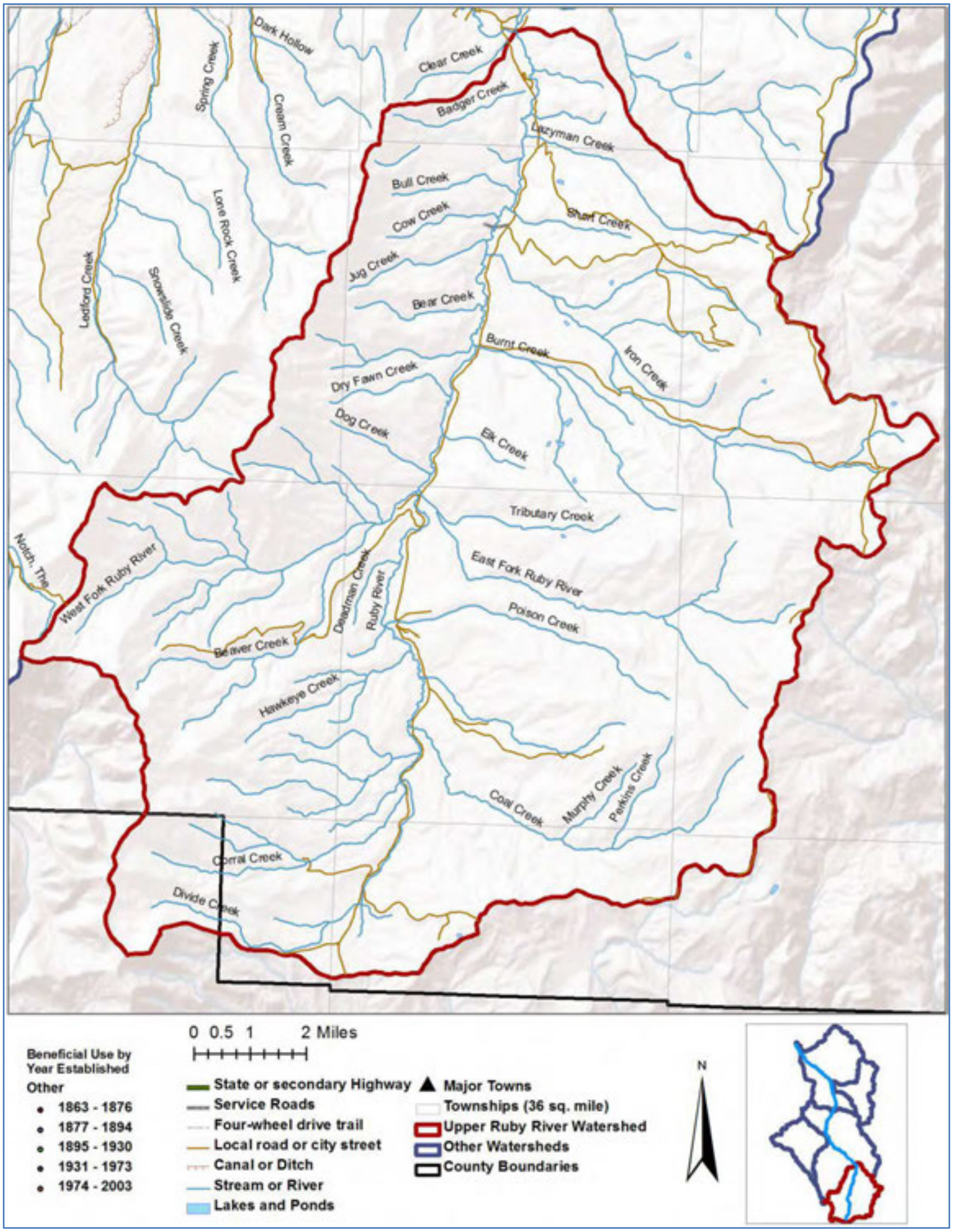


Figure 17 Detail Map of Upper Ruby River Watershed showing Other Points of Use

APPENDIX F: MAP SERIES OF BENEFICIAL USES IN MIDDLE RUBY RIVER WATERSHED

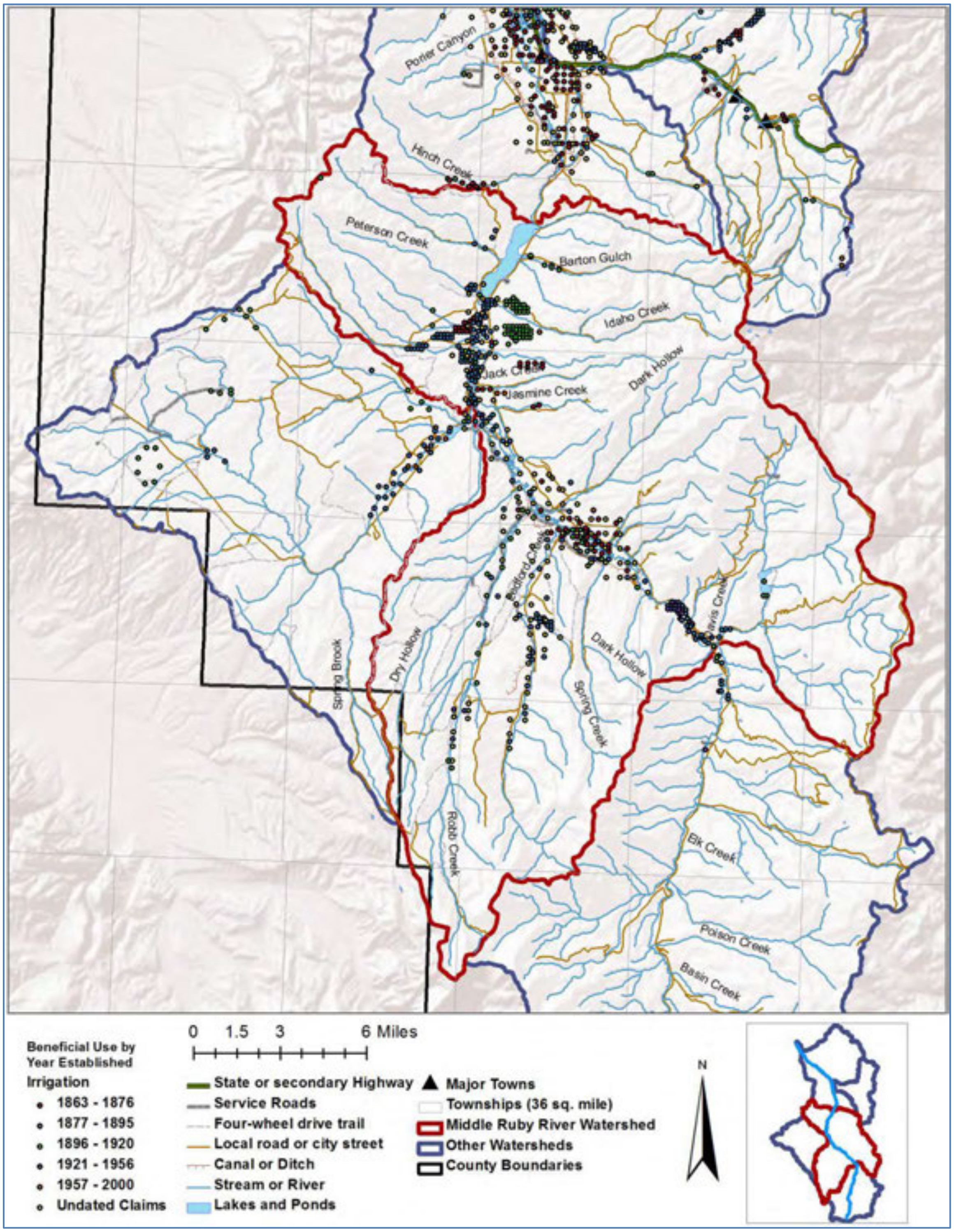


Figure 18 Detail Map of Middle Ruby River Watershed showing Irrigation Points of Use

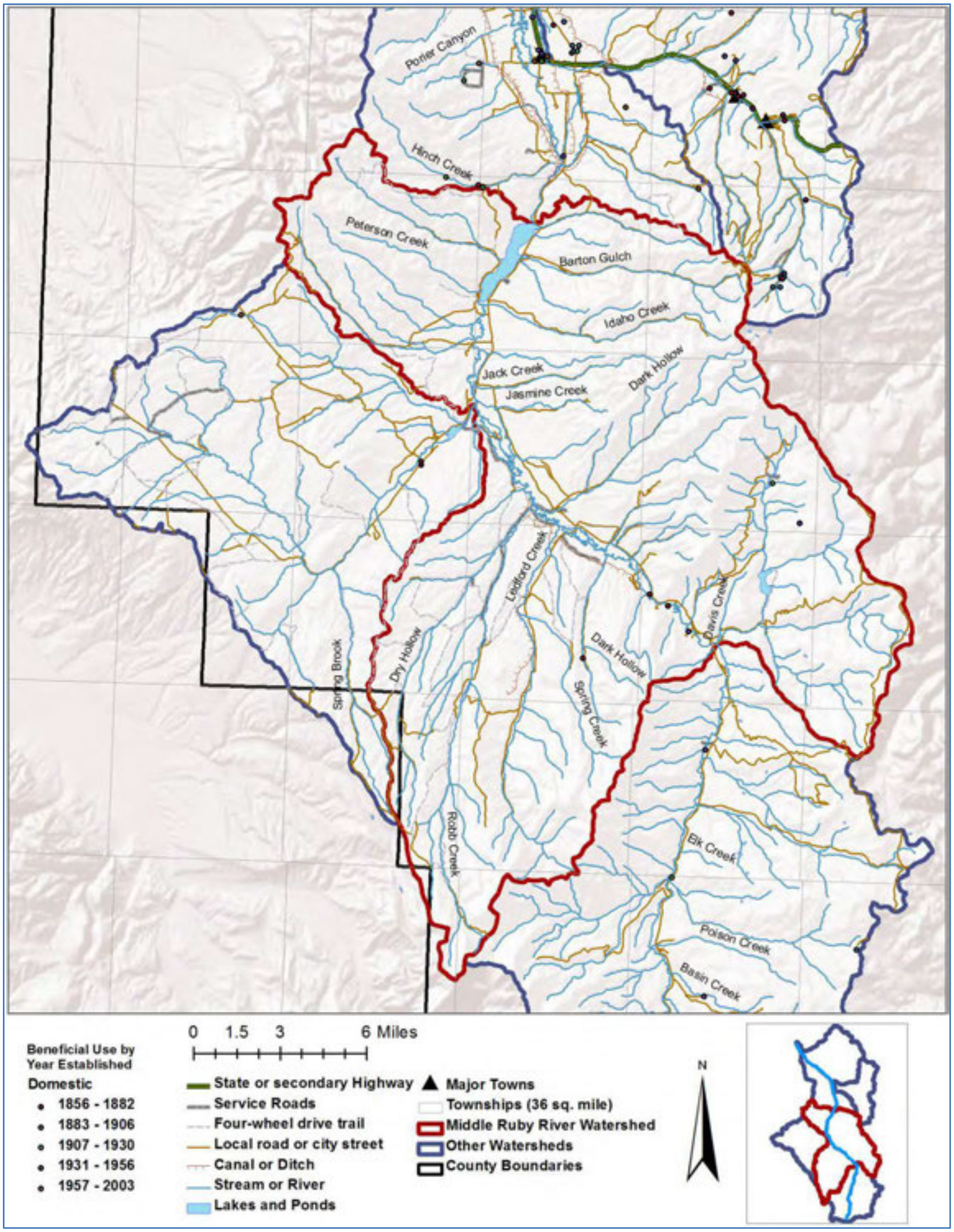


Figure 19 Detail Map of Middle Ruby River Watershed showing Domestic Points of Use

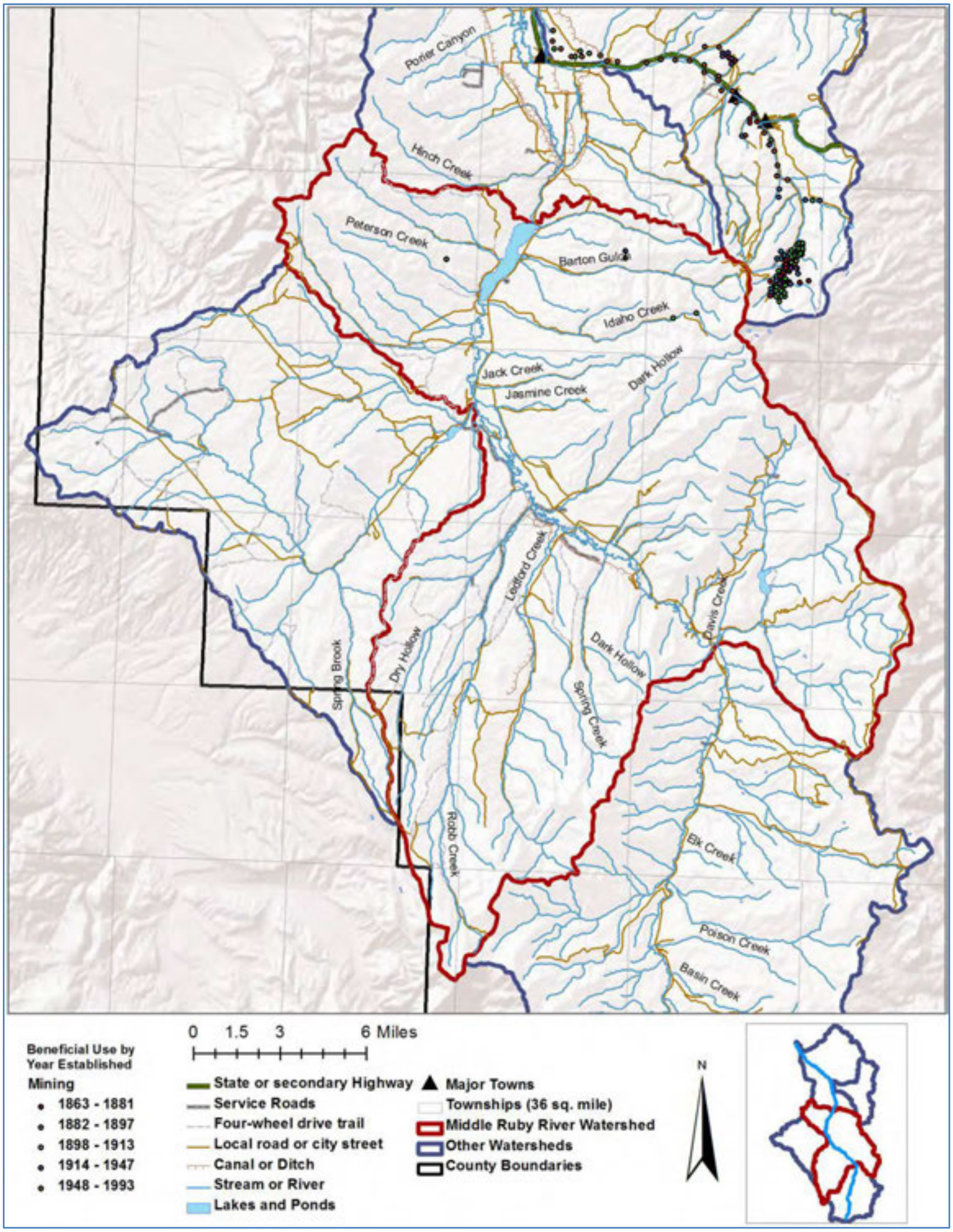


Figure 20 Detail Map of Middle Ruby River Watershed showing Mining Points of Use

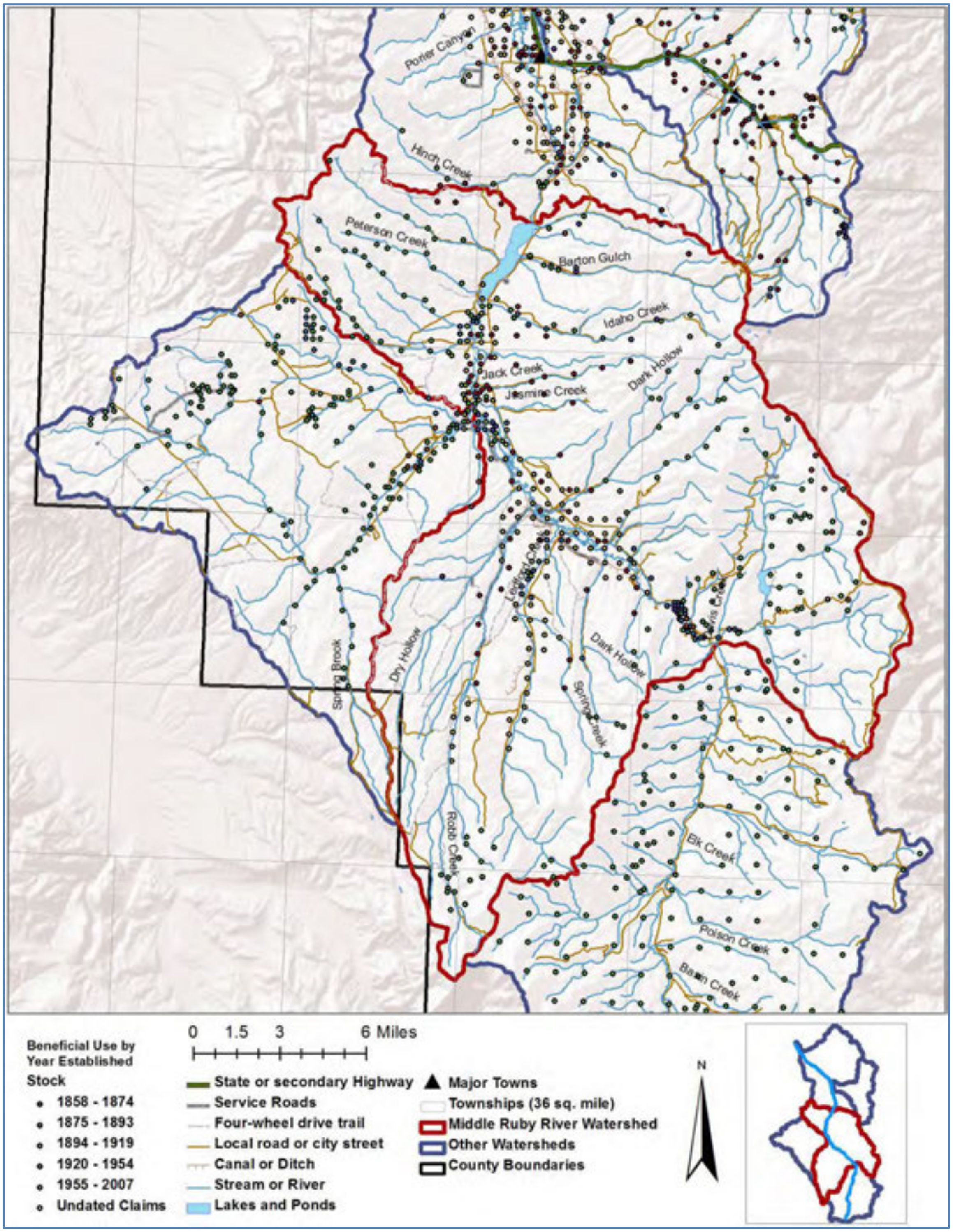


Figure 21 Detail Map of Middle Ruby River Watershed showing Stock Points of Use

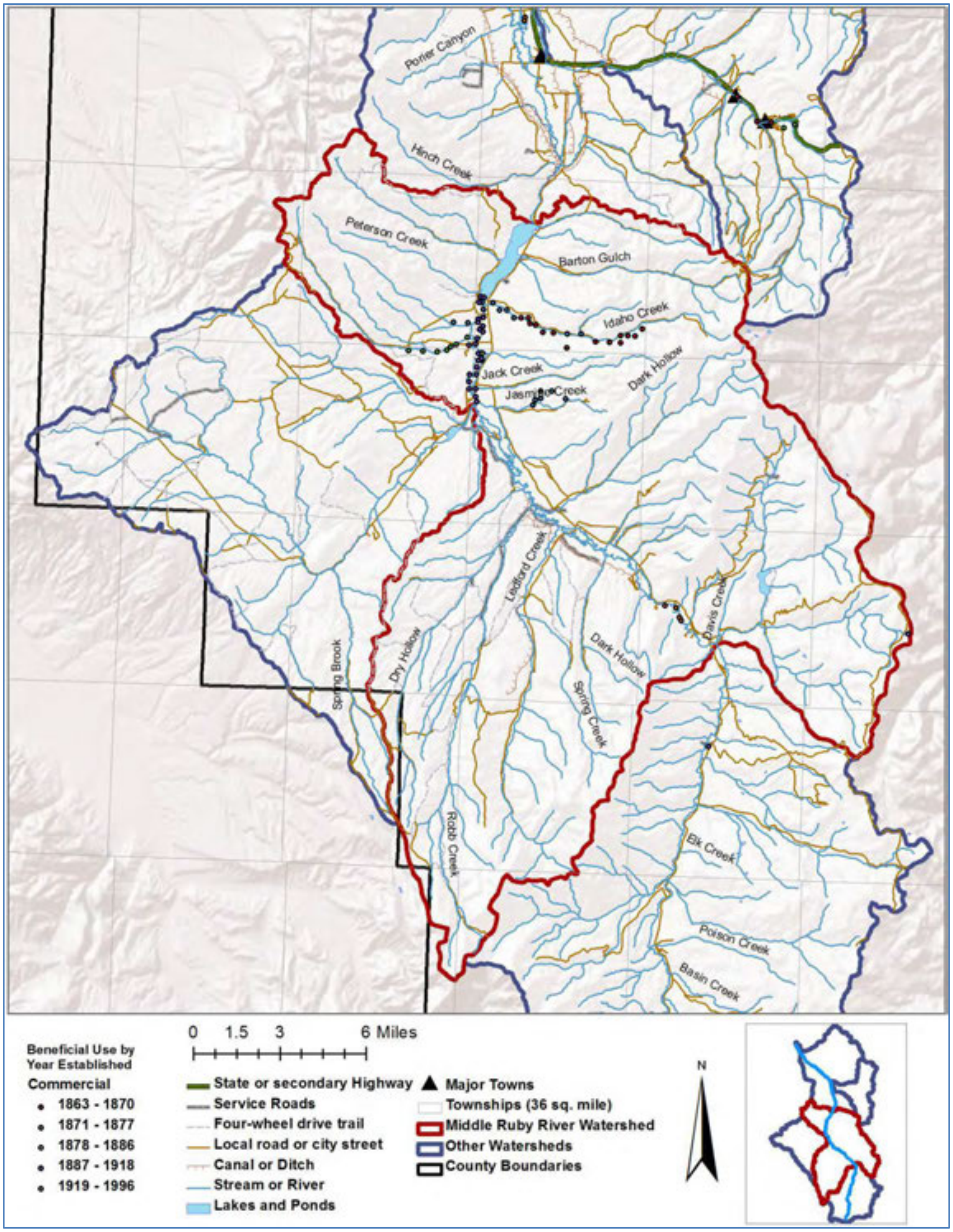


Figure 22 Detail Map of Middle Ruby River Watershed showing Commercial Points of Use

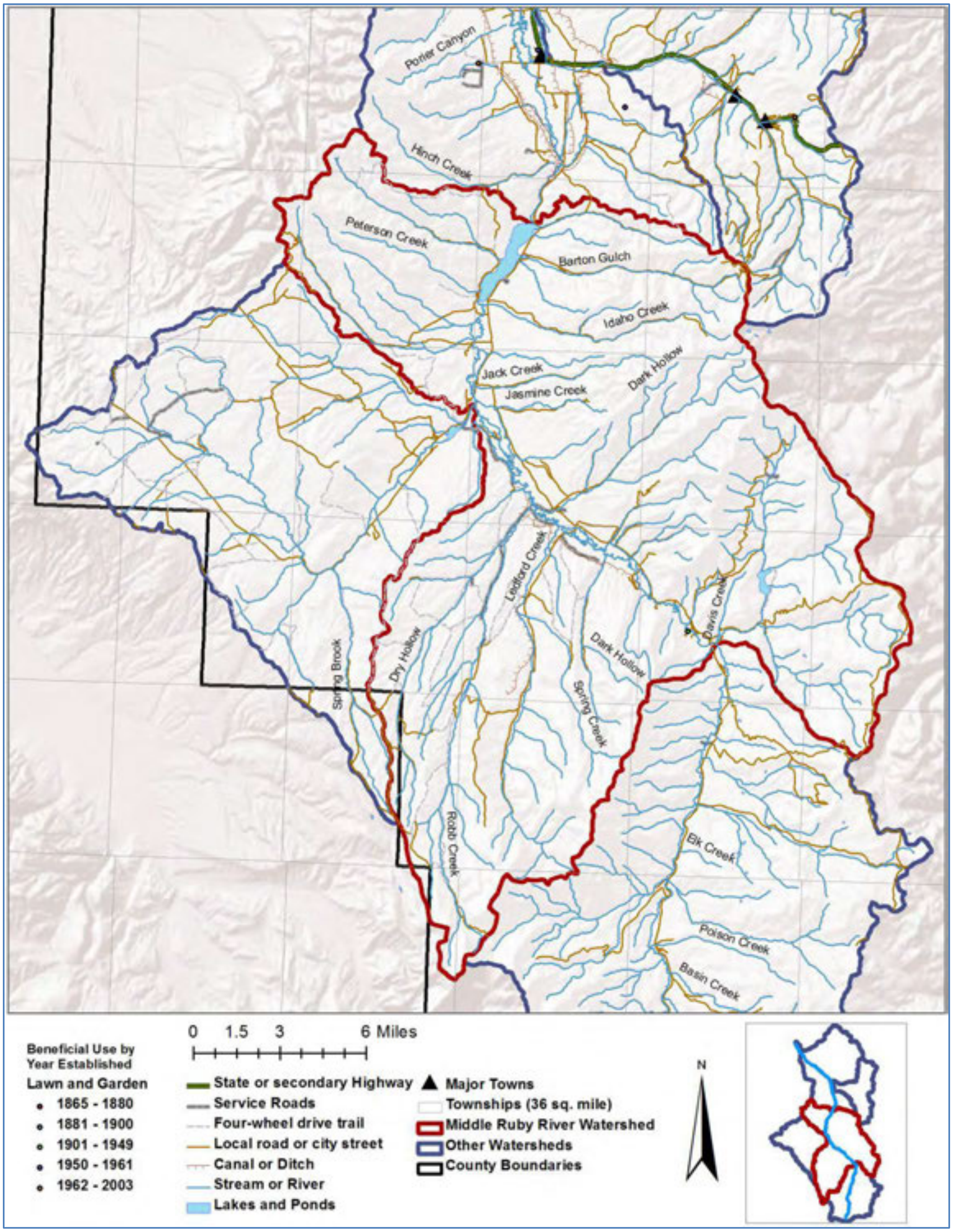


Figure 23 Detail Map of Middle Ruby River Watershed showing Lawn and Garden Points of Uses

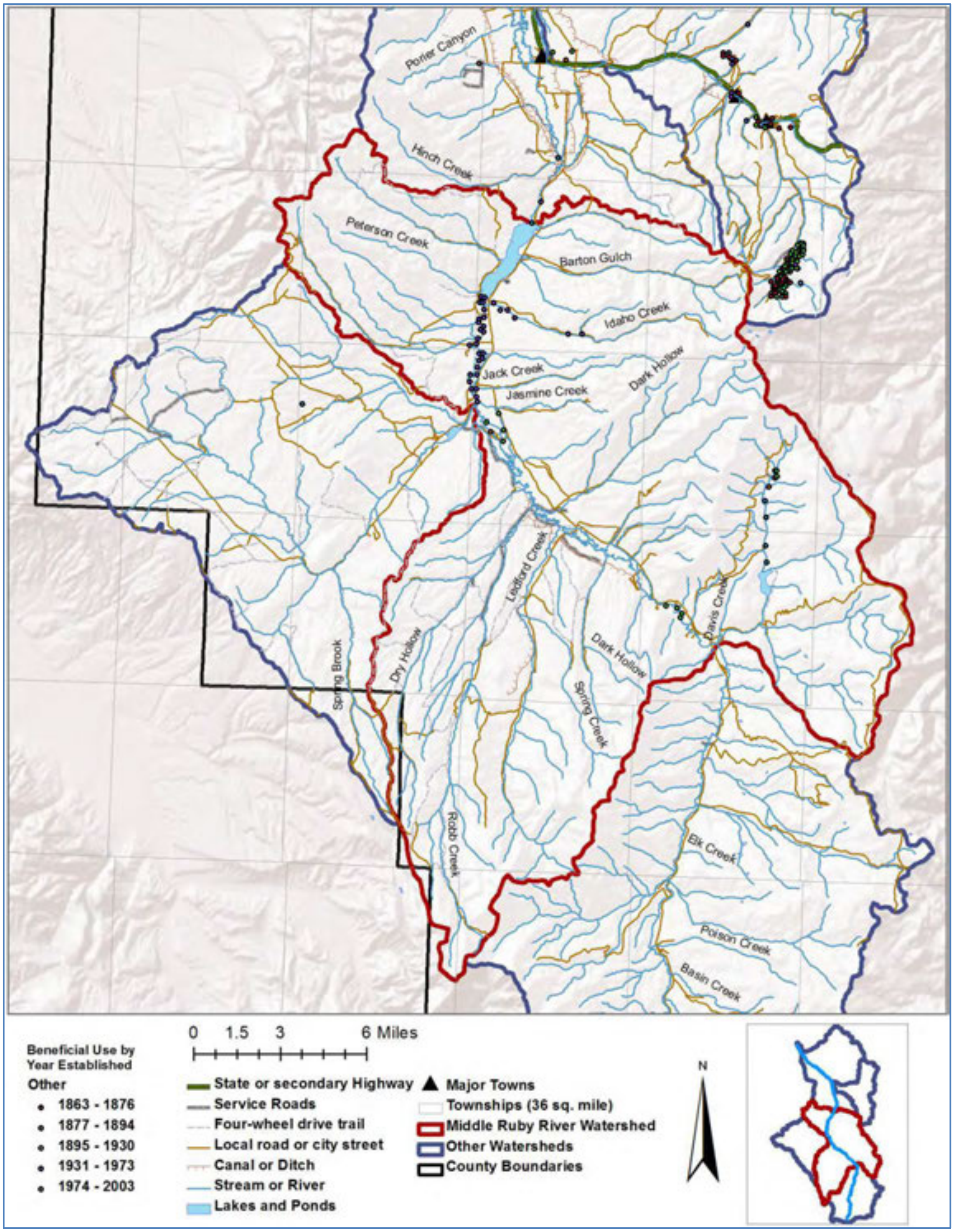


Figure 24 Detail Map of Middle Ruby River Watershed showing Other Points of Use

APPENDIX G: MAP SERIES OF BENEFICIAL USES IN LOWER RUBY RIVER WATERSHED

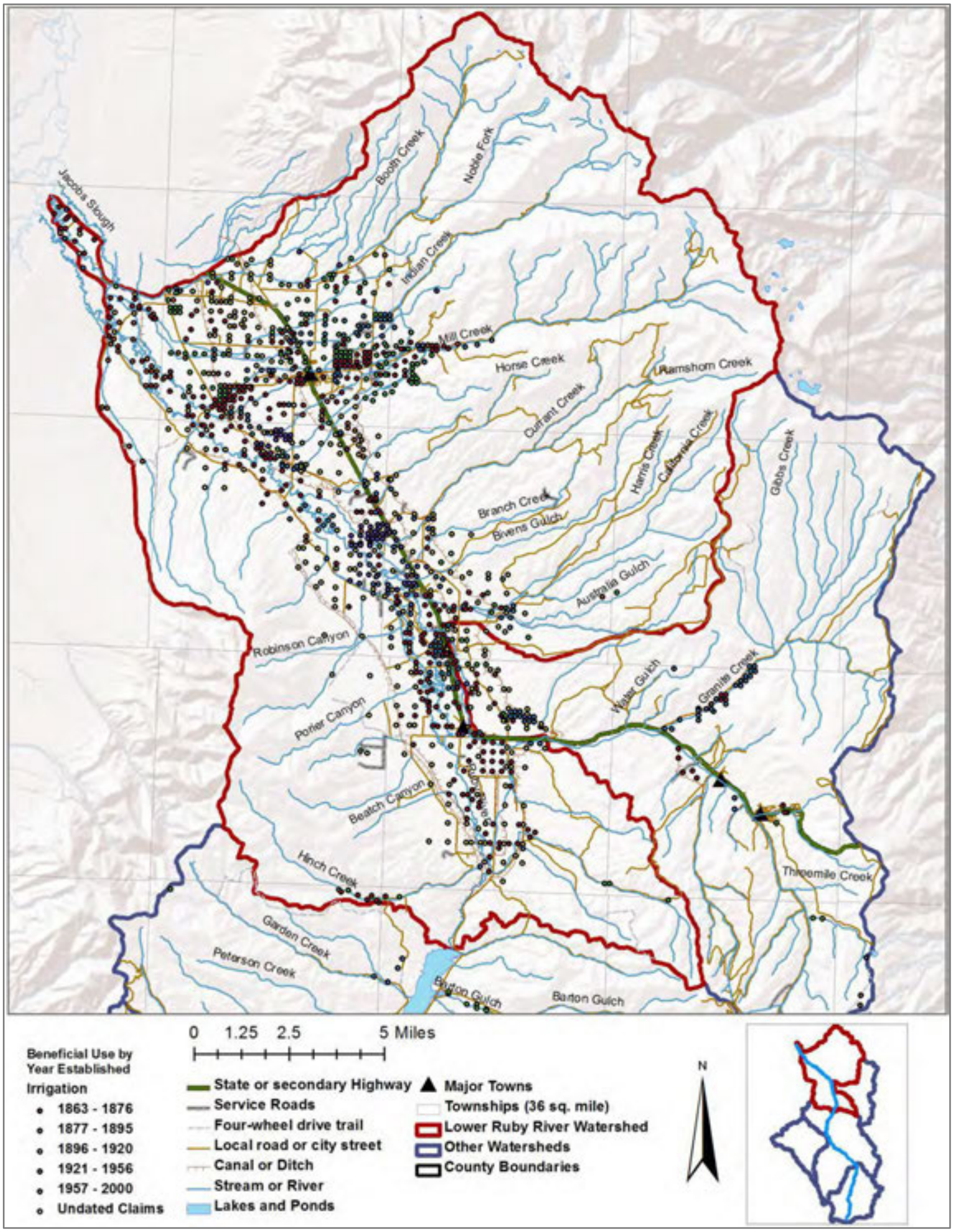


Figure 25 Detail Map of Lower Ruby River Watershed showing Irrigation Points of Use

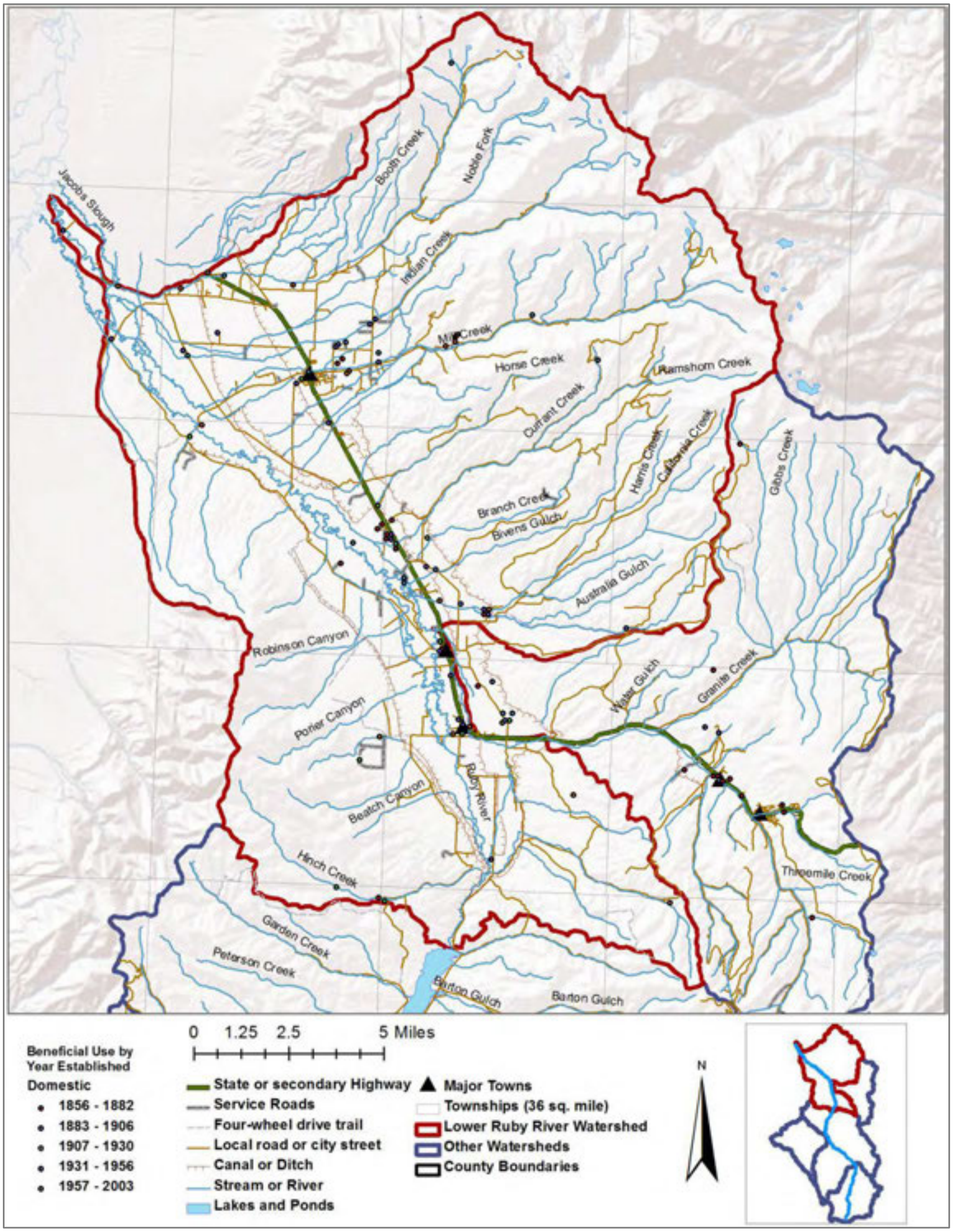


Figure 26 Detail Map of Lower Ruby River Watershed showing Domestic Points of Use

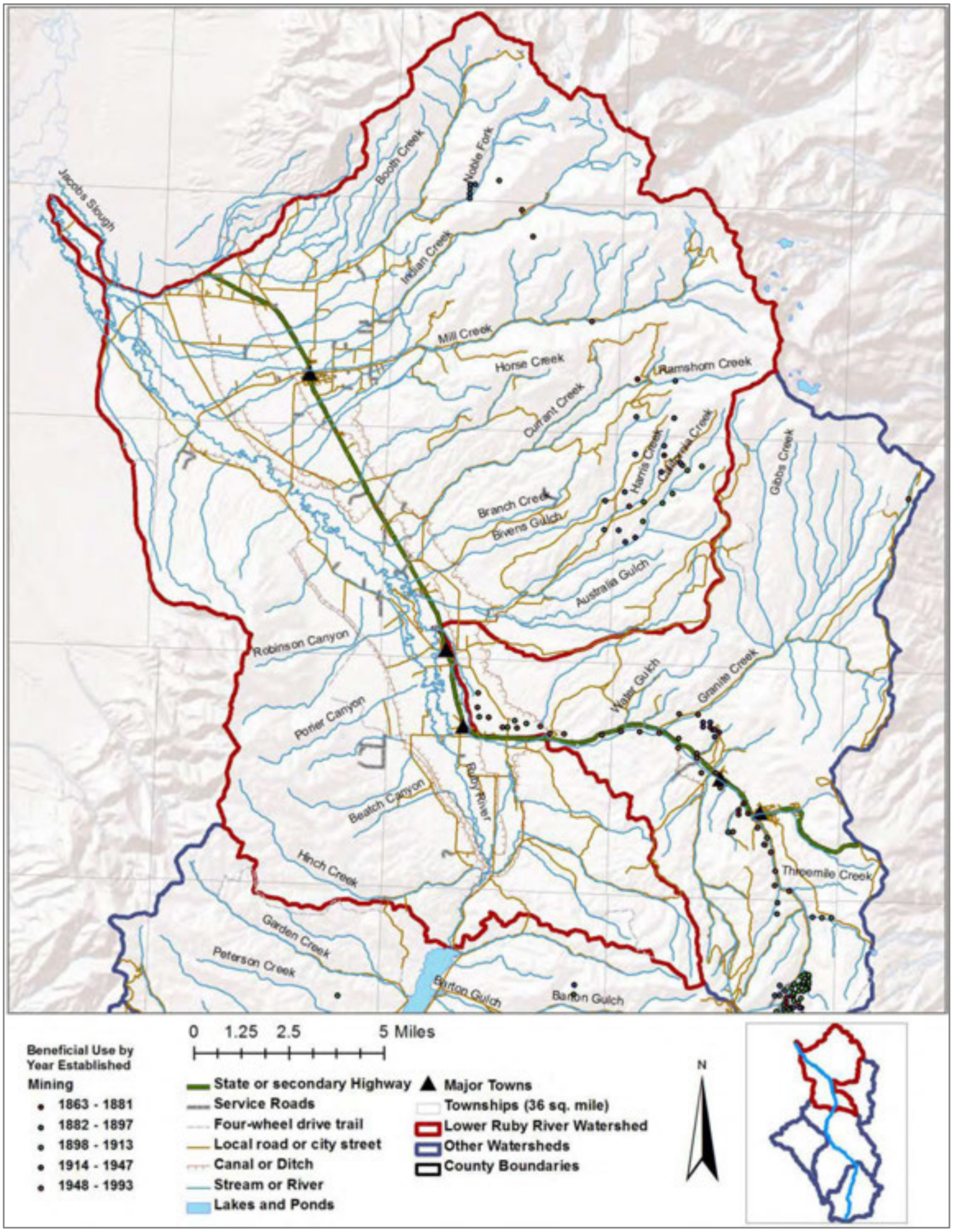


Figure 27 Detail Map of Lower Ruby River Watershed showing Mining Points of Use

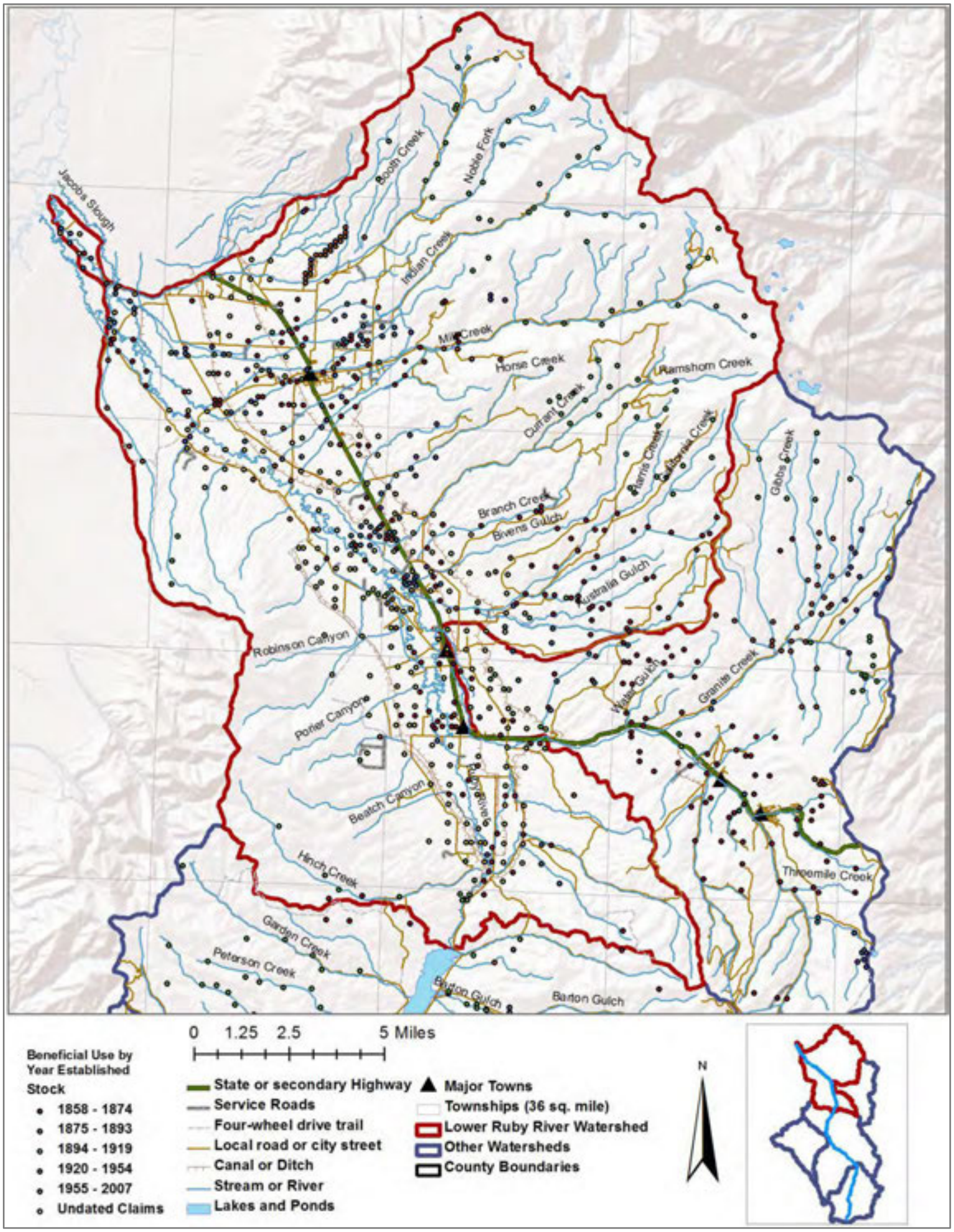


Figure 28 Detail Map of Lower Ruby River Watershed showing Stock Points of Use

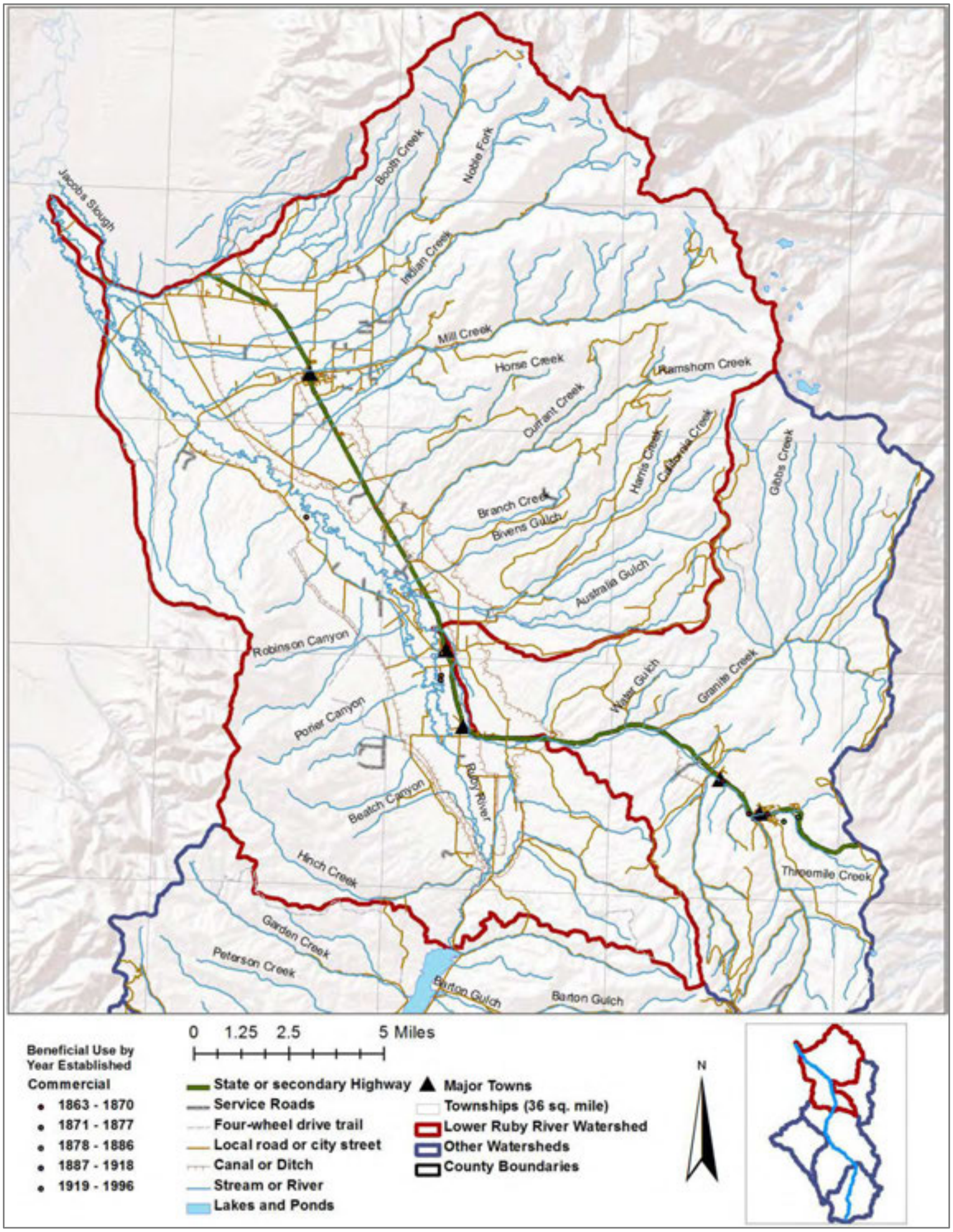


Figure 29 Detail Map of Lower Ruby River Watershed showing Commercial Points of Use

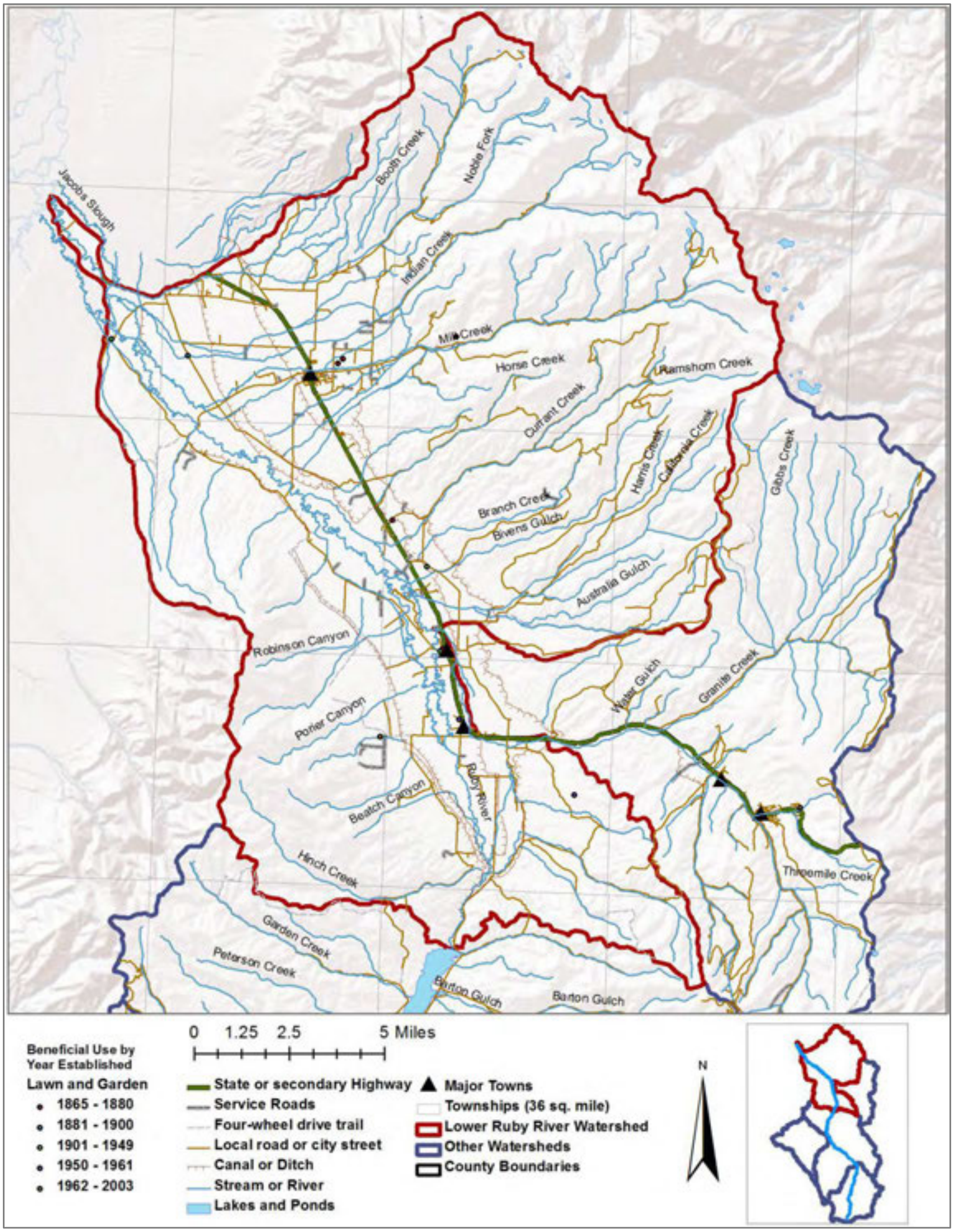


Figure 30 Detail Map of Lower Ruby River Watershed showing Lawn and Garden Points of Use

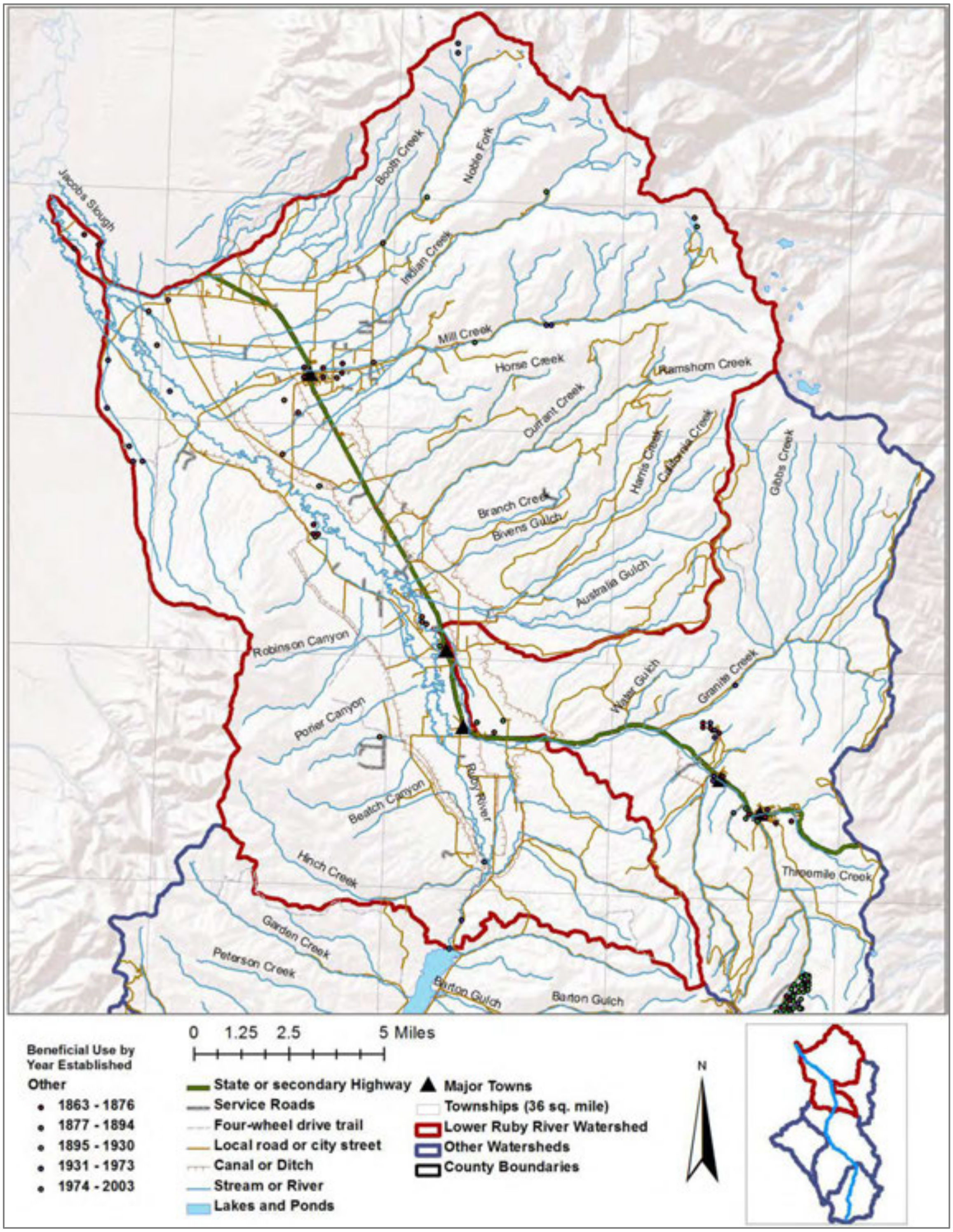


Figure 31 Detail Map of Lower Ruby River Watershed showing Other Points of Use

APPENDIX H: MAP SERIES OF BENEFICIAL USES IN SWEETWATER CREEK WATERSHED

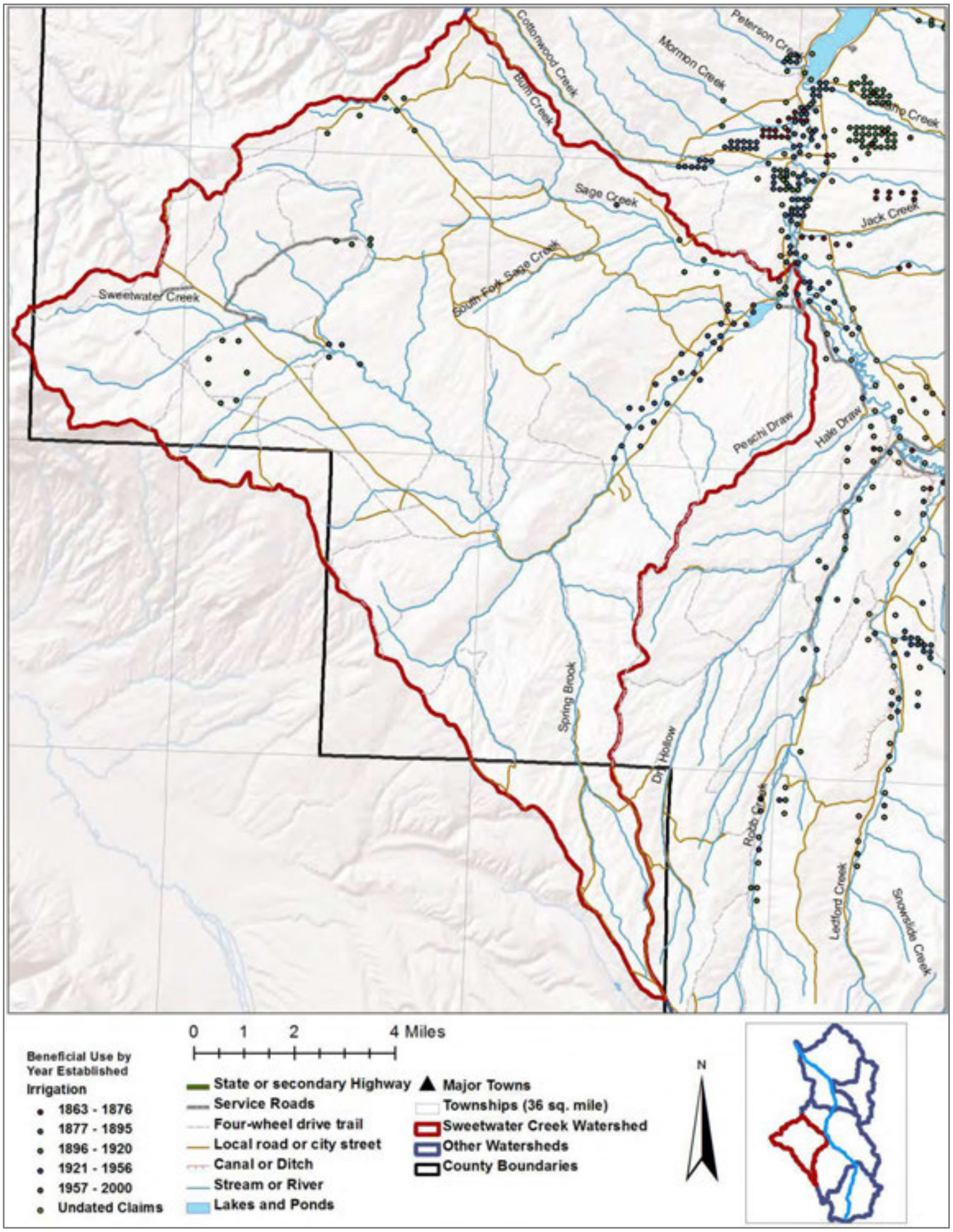


Figure 32 Detail Map of Sweetwater Creek Watershed showing Irrigation Points of Use

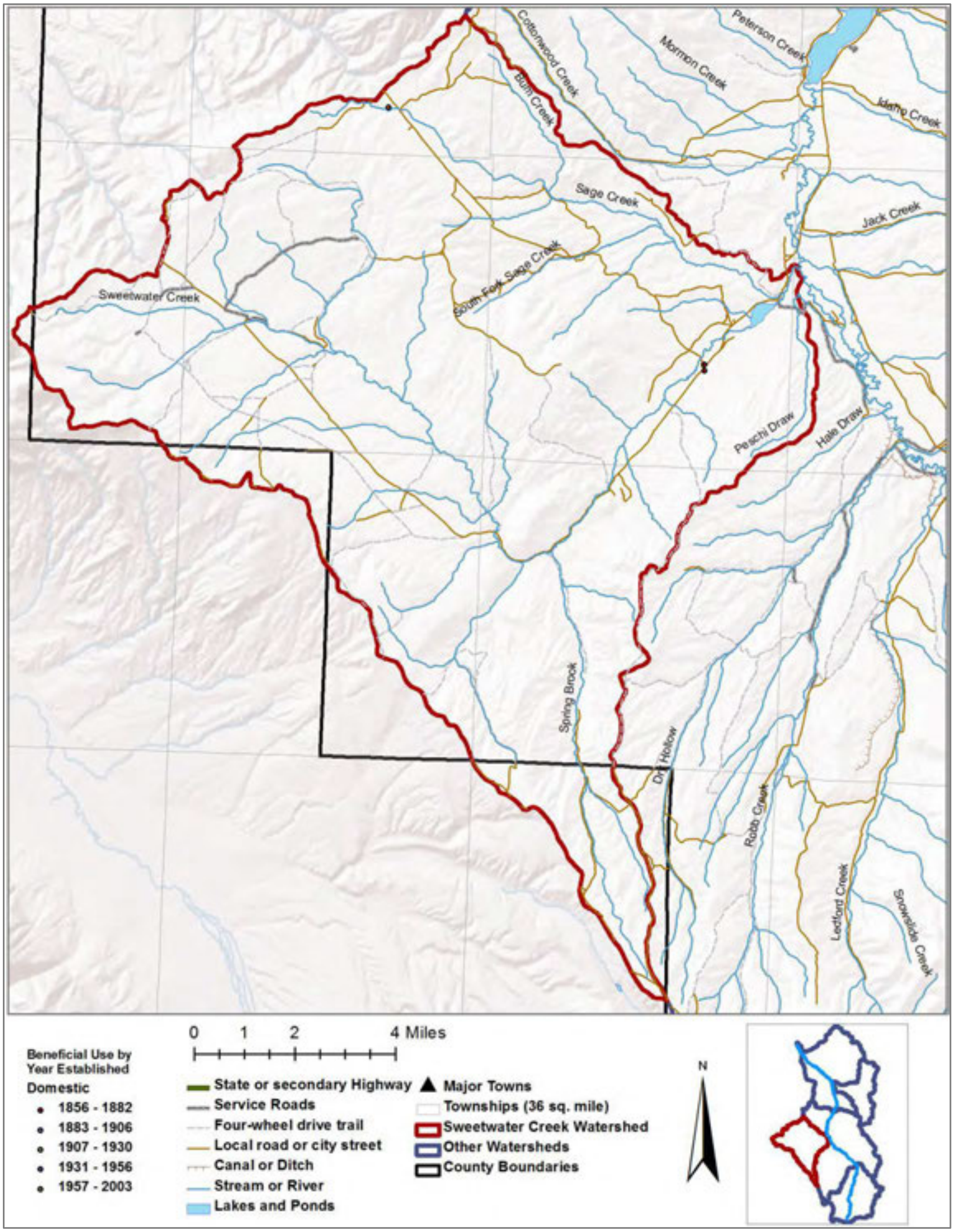


Figure 33 Detail Map of Sweetwater Creek Watershed showing Domestic Points of Use

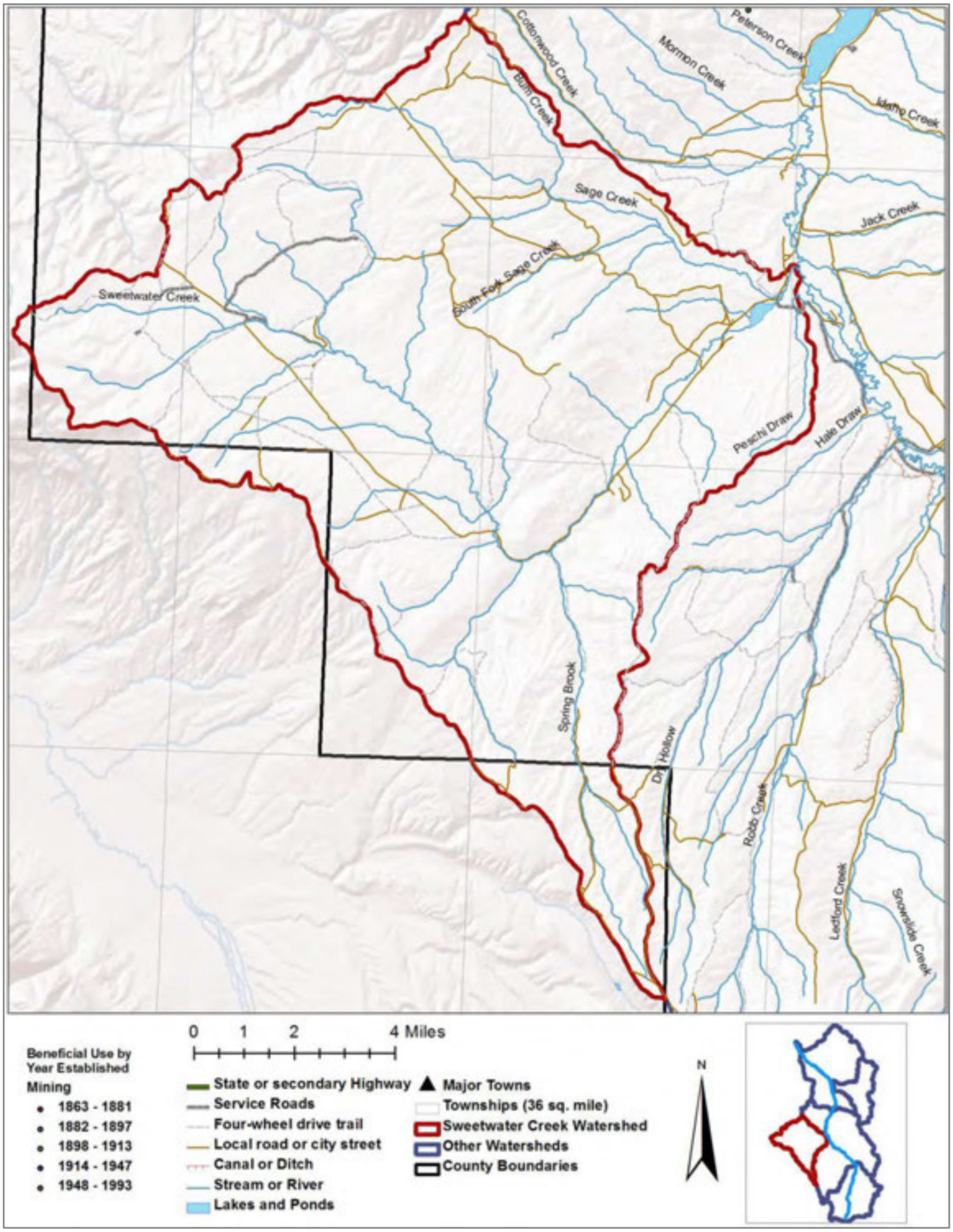


Figure 34 Detail Map of Sweetwater Creek Watershed showing Mining Points of Use

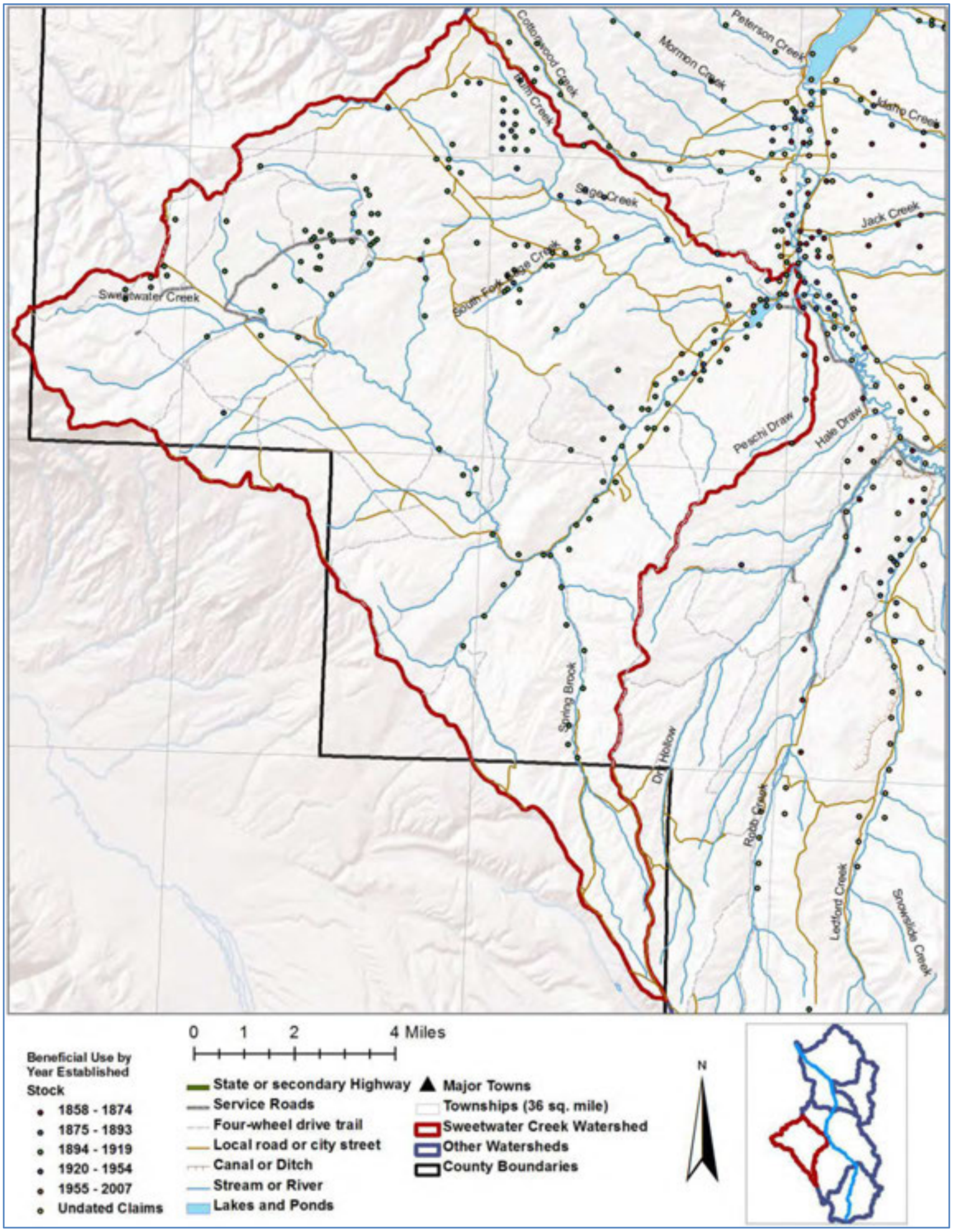


Figure 35 Detail Map of Sweetwater Creek Watershed showing Stock Points of Use

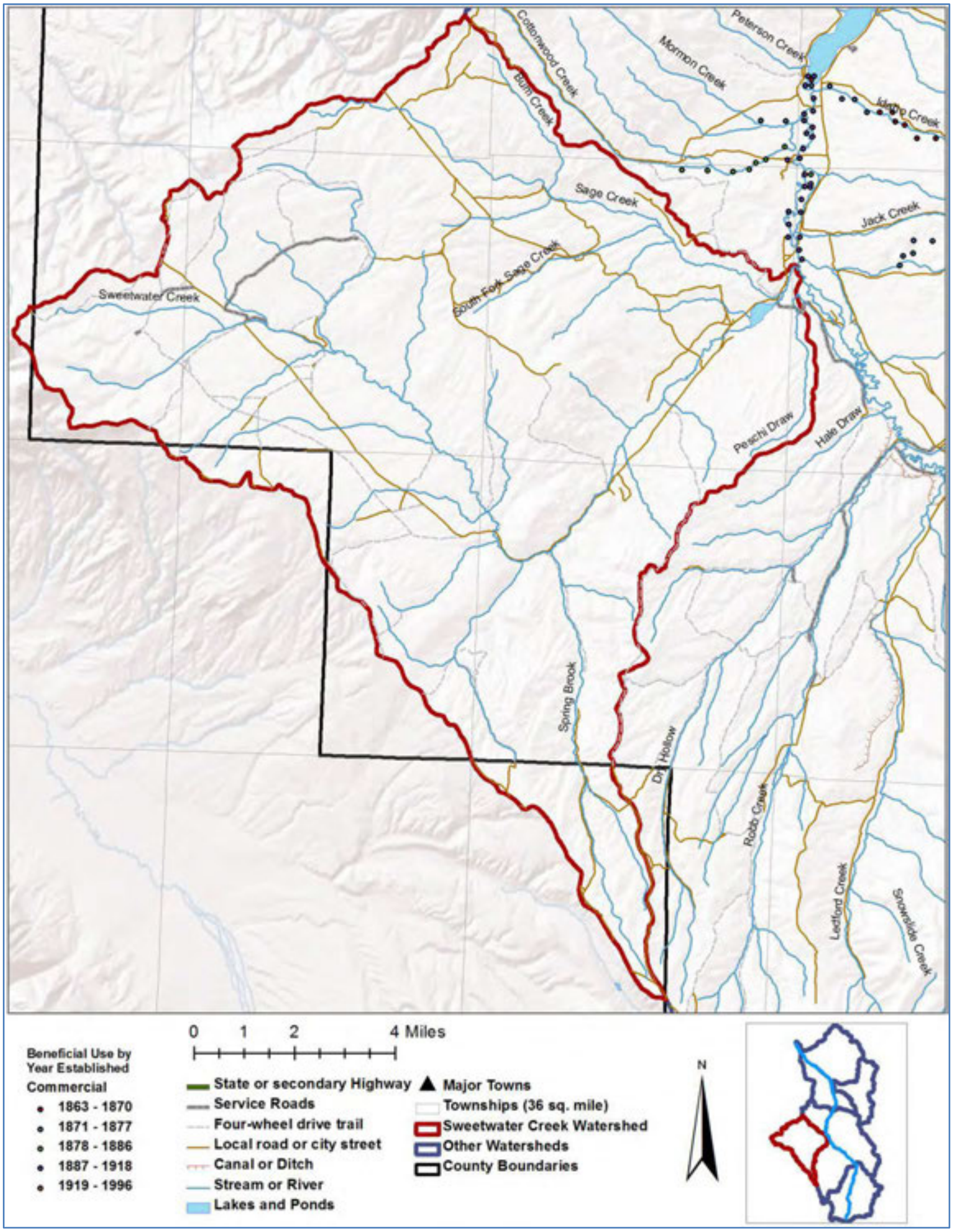


Figure 36 Detail Map of Sweetwater Creek Watershed showing Commercial Points of Use

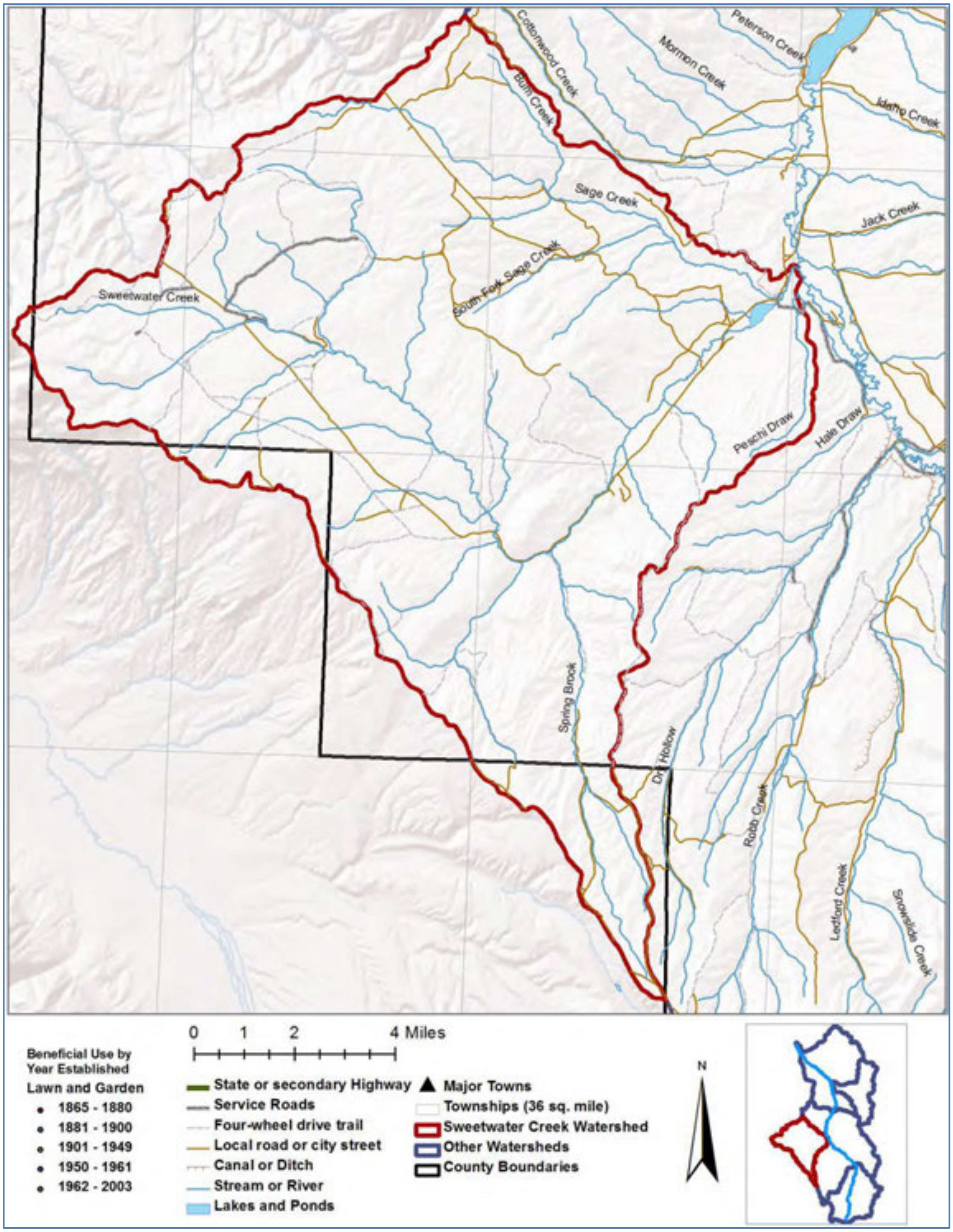


Figure 37 Detail Map of Sweetwater Creek Watershed showing Lawn and Garden Points of Use

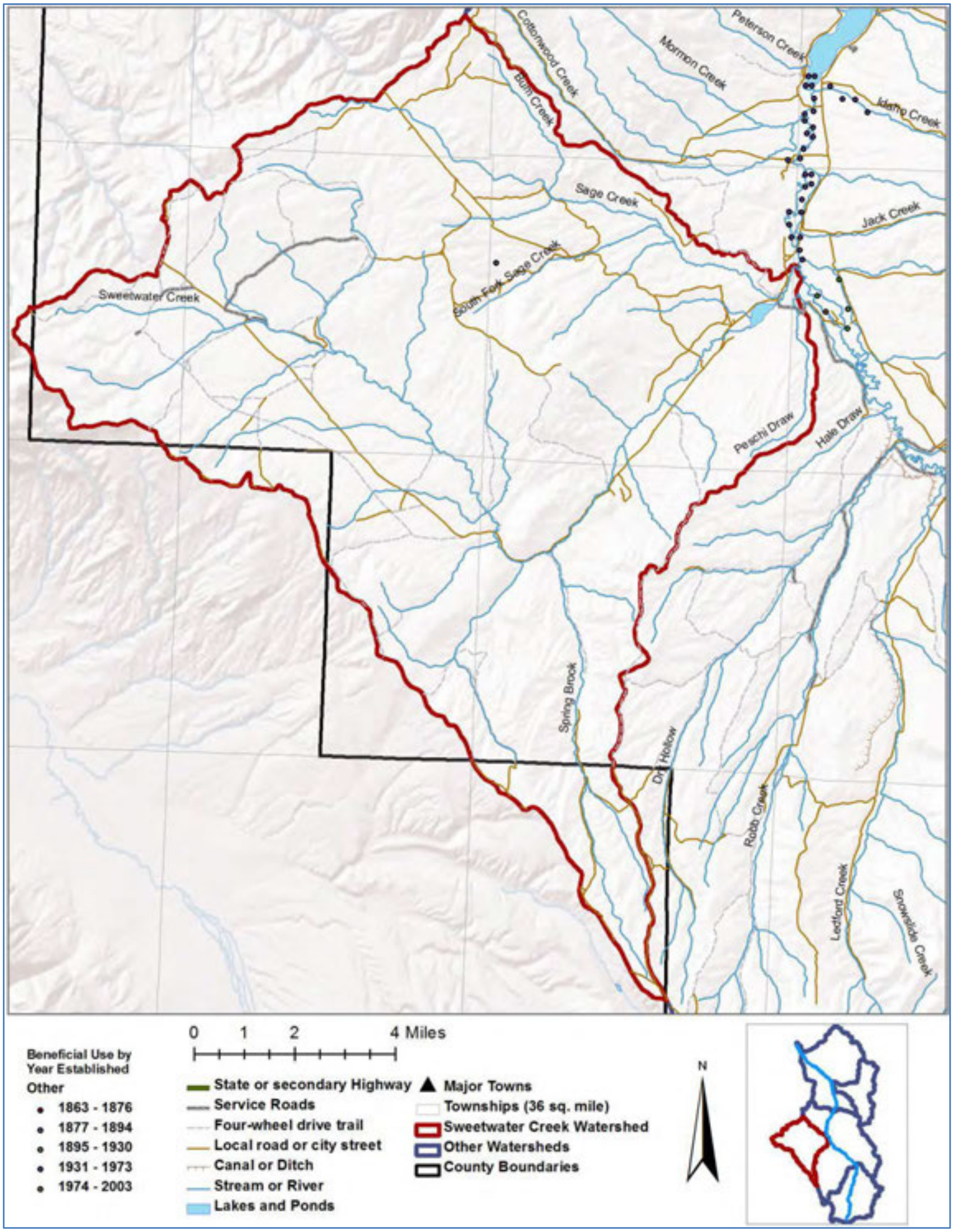


Figure 38 Detail Map of Sweetwater Creek Watershed showing Other Points of Use

APPENDIX I: MAP SERIES OF BENEFICIAL USES IN ALDER GULCH WATERSHED

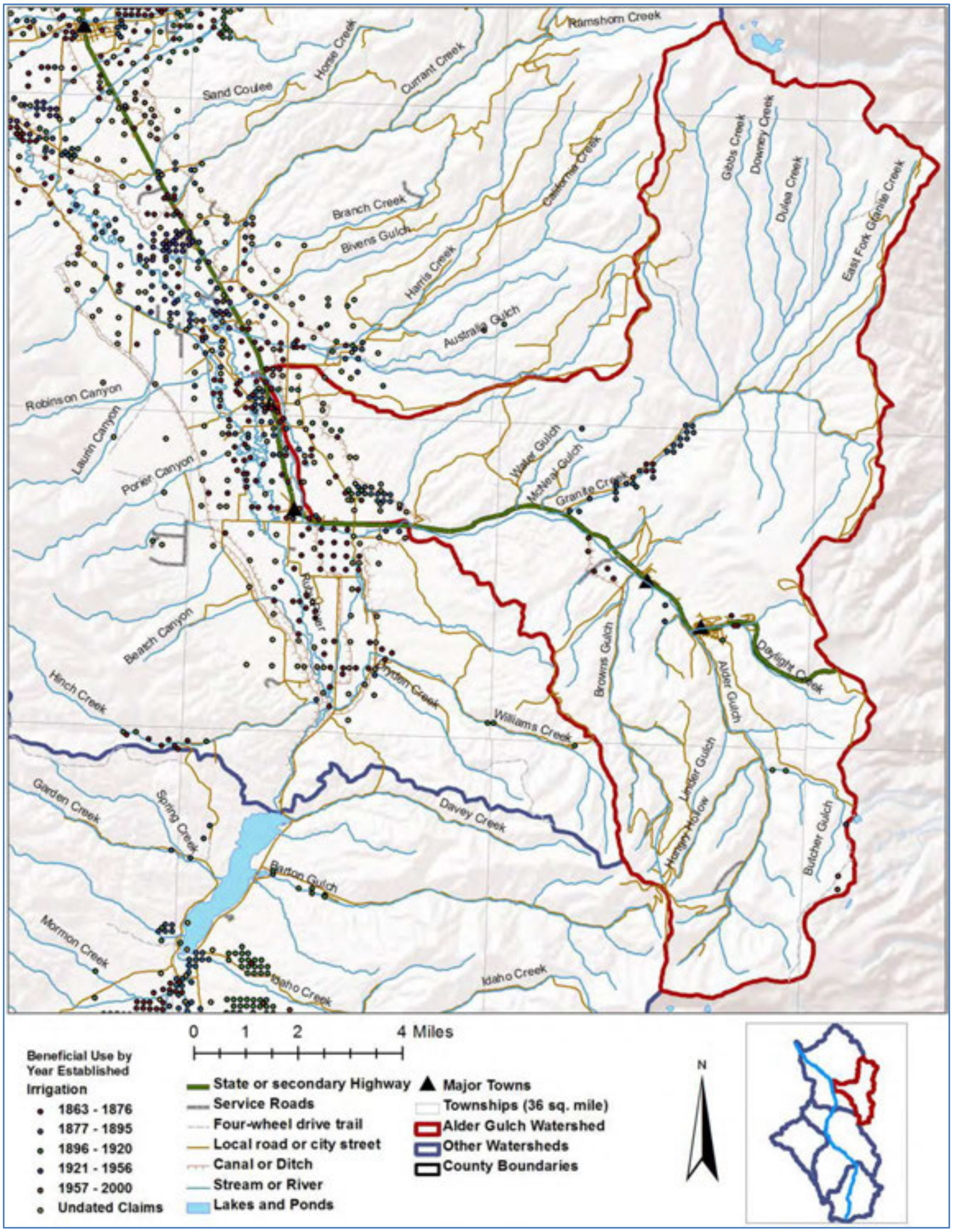


Figure 39 Detail Map of Alder Gulch Watershed showing Irrigation Points of Use

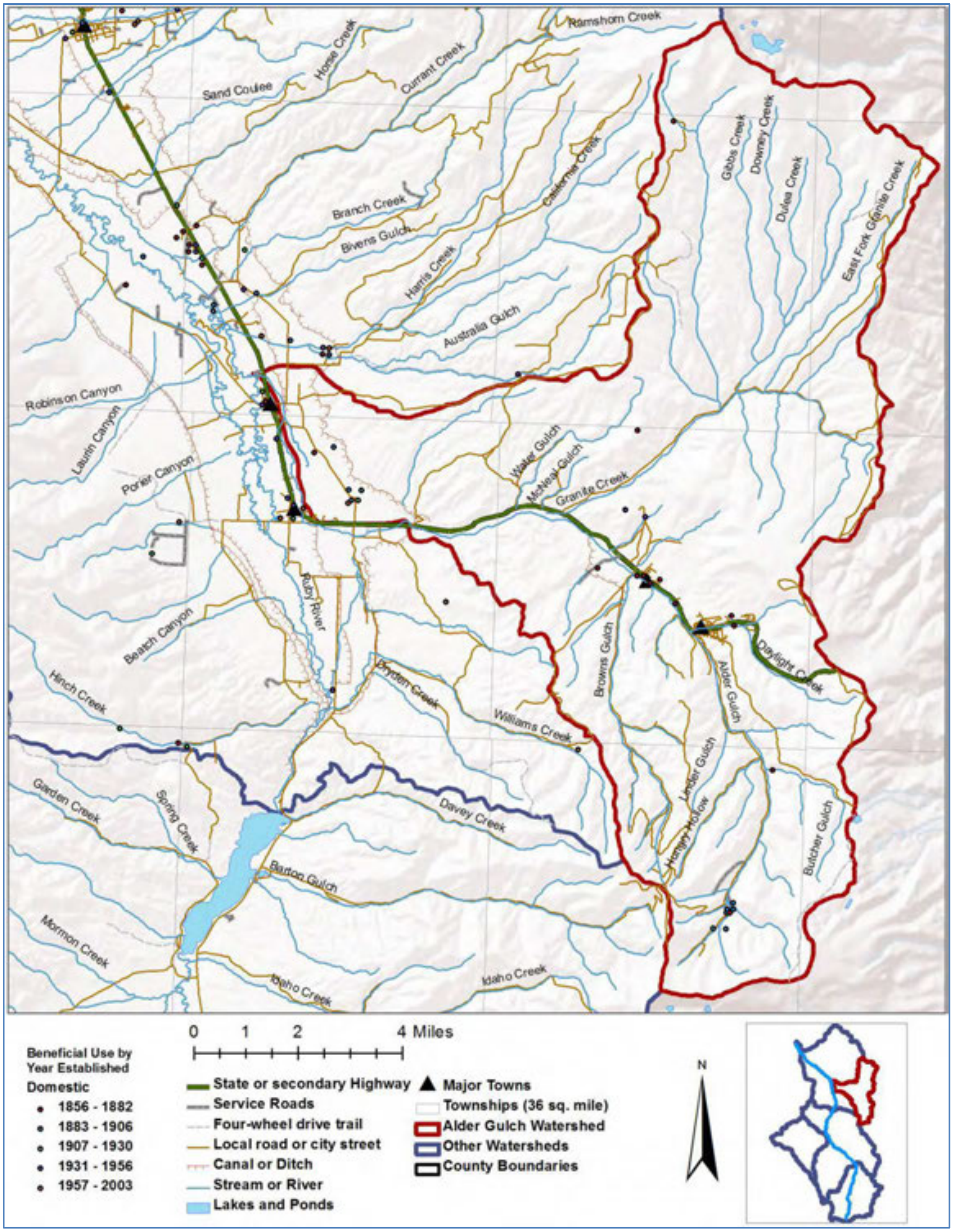


Figure 40 Detail Map of Alder Gulch Watershed showing Domestic Points of Use

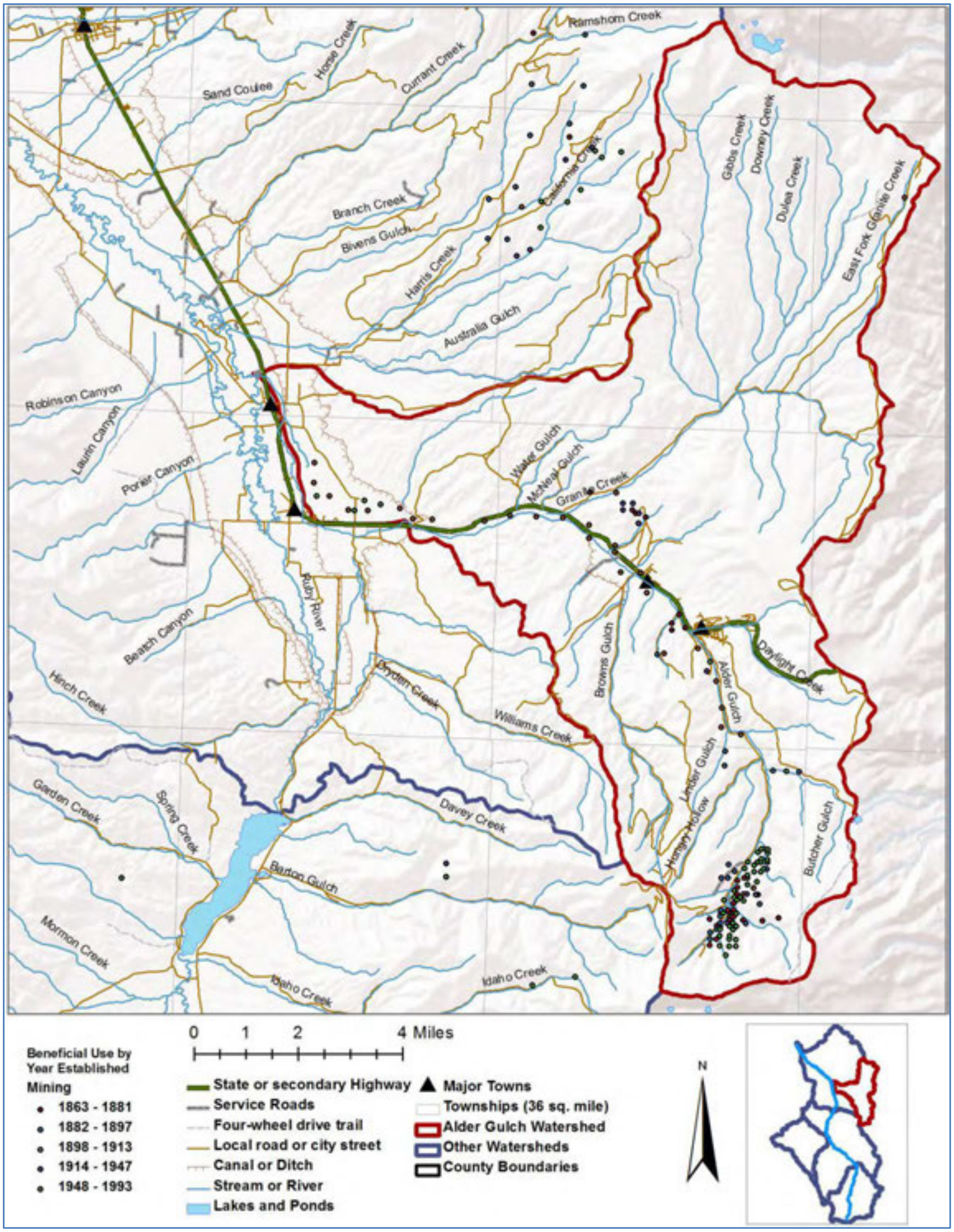


Figure 41 Detail Map of Alder Gulch Watershed showing Mining Points of Use

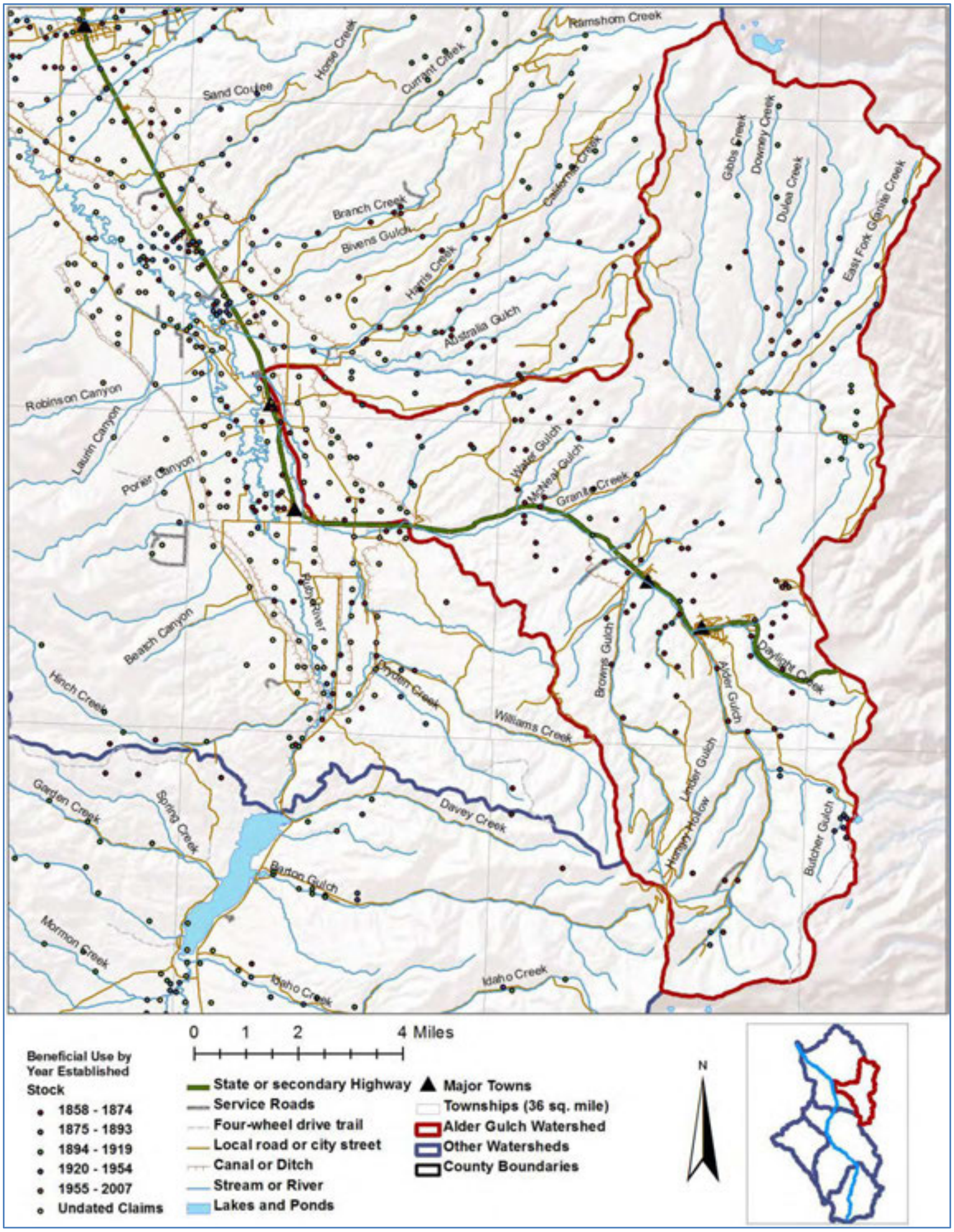


Figure 42 Detail Map of Alder Gulch Watershed showing Stock Points of Use

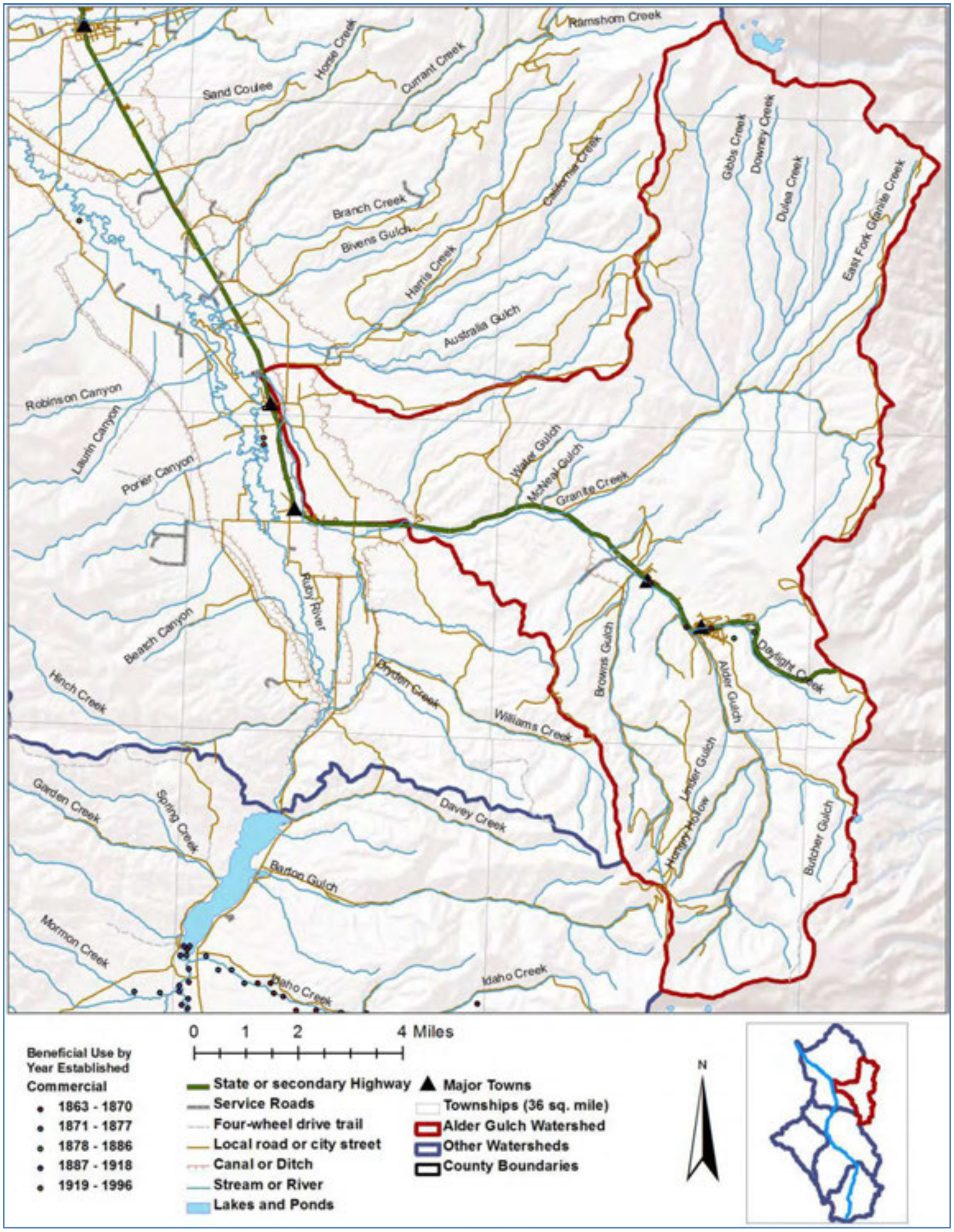


Figure 43 Detail Map of Alder Gulch Watershed showing Commercial Points of Use

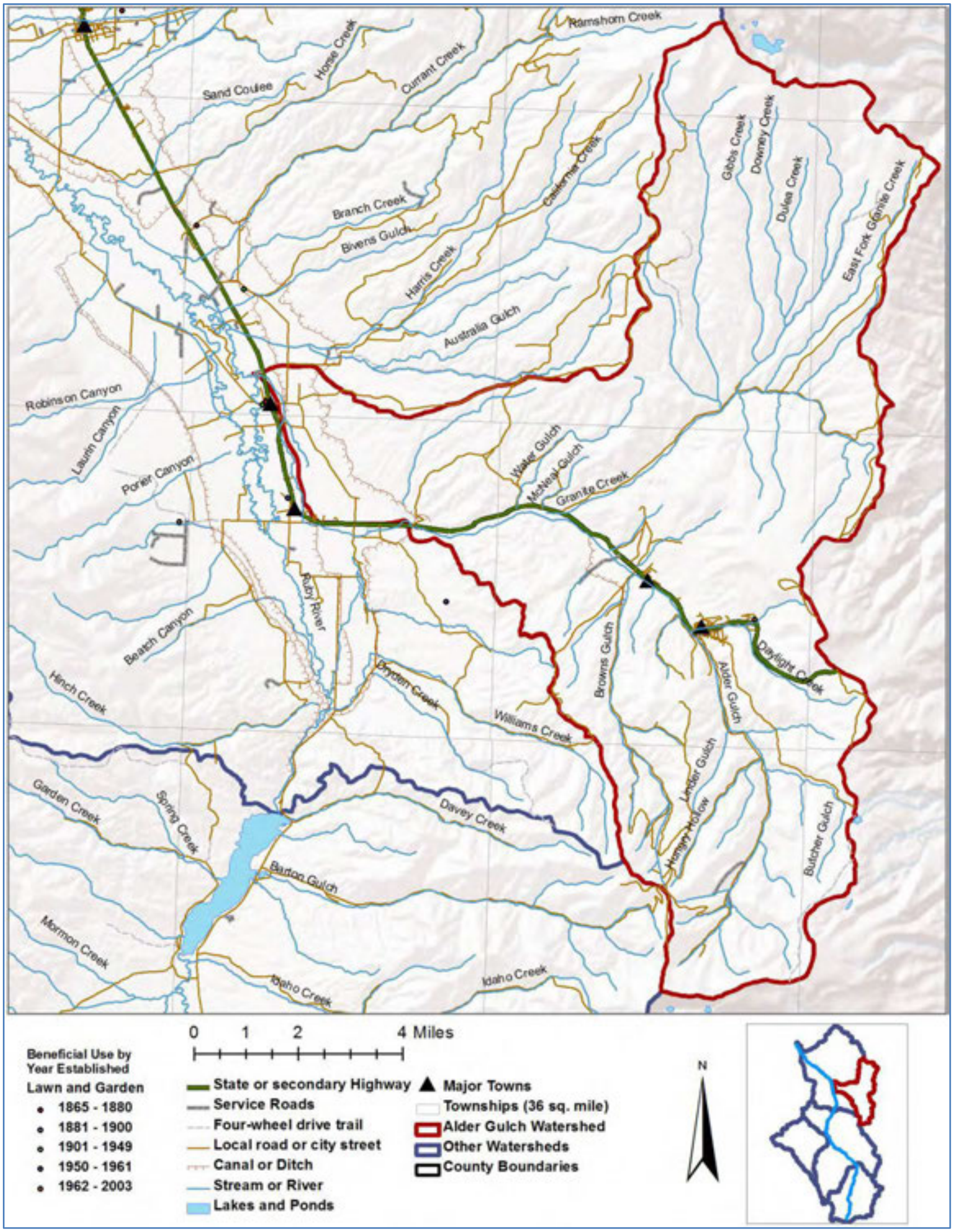


Figure 44 Detail Map of Alder Gulch Watershed showing Lawn and Garden Points of Use

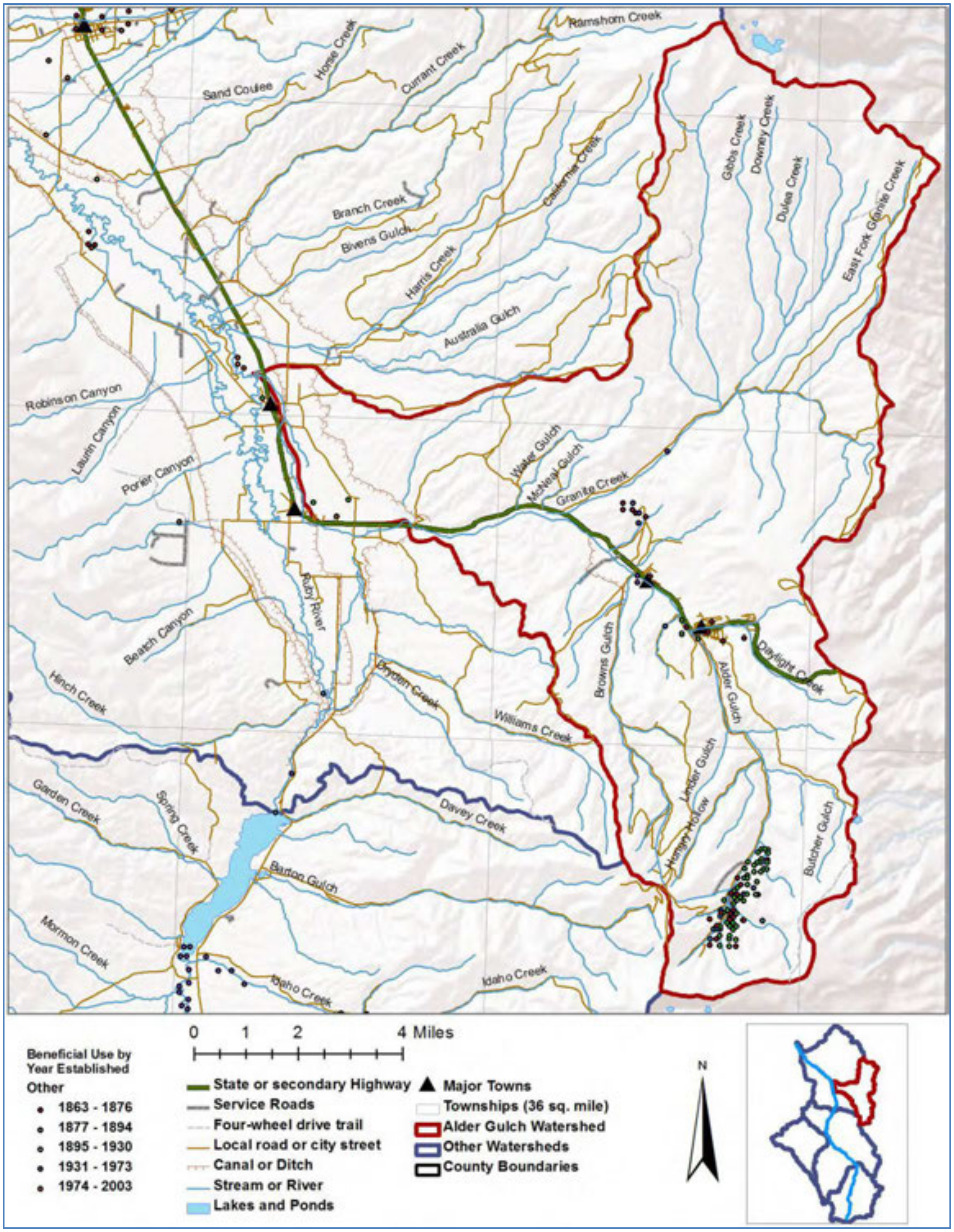


Figure 45 Detail Map of Alder Gulch Watershed showing Other Points of Use