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Development of a High-Resolution Land Cover Dataset to Support Integrated Water Resources Planning and Management in Northern Utah

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DEVELOPMENT OF A HIGH-RESOLUTION LAND COVER DATASET

TO SUPPORT INTEGRATED WATER RESOURCES PLANNING

AND MANAGEMENT IN NORTHERN UTAH

by

Ellie Irene Leydsman McGinty

A thesis submitted in partial fulfillment
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ABSTRACT

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by

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Utah State University, 2020

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Integrated approaches to planning and management have become indispensable strategies for balancing environmental sustainability and integrity with human development and activities. Integrated approaches have emerged out of the need to resolve the wide range of complex and interconnected challenges that span multiple jurisdictions. The state of Utah, located in the arid Intermountain West, has recently been recognized as the fastest growing state in the nation. State agencies and planning entities will require innovative integrated approaches to resolve the various issues associated with water resources degradation and depletion. The degradation and depletion of valuable water resources have been and continue to be significant issues in Utah. With growing shortages and an increase in environmental awareness, state agencies have started to support more balanced solutions to water resources management. In recent decades, Utah agencies have espoused more integrated approaches to water resources planning and management. Current water resources activities that support integrated action include (1) the development of a comprehensive state water plan and detailed river basin plans; (2) the implementation of Utah's Watershed Approach to managing and reducing nonpoint source pollution; and (3) the establishment of an integrated approach to wetland management through Utah's Wetland Program Plan. Successful implementation of these plans and programs remains complicated. However, geospatial technologies can significantly enhance planning and management processes. Geospatial technologies have enabled land use planners and managers to develop detailed and spatially explicit land cover information for the purpose of supporting improved understanding and decision-making. Therefore, through a United States Environmental Protection Agency Region 8 Wetland Program Development Grant, a high-resolution land cover dataset, with a primary emphasis on mapping and quantifying impervious surfaces, was developed for three watershed sub-basins in northern Utah to support integrated water resources planning and management. This high-resolution land cover dataset can serve as an indicator of cumulative stress from urbanization; it can support the development of ecologically relevant metrics that can be integrated into watershed health and wetland condition assessments; it can provide general assessments of watershed condition; and it can support the identification of sites in need of restoration and protection.

(217 pages)

PUBLIC ABSTRACT

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Integrated planning and management approaches, including bioregional planning and integrated water resources planning, are comprehensive strategies that strive to balance the sustainability of natural resources and the integrity of ecosystem processes with human development and activities. Implementation of integrated plans and programs remains complicated. However, geospatial technologies, such as geographic information systems and remote sensing, can significantly enhance planning and management processes.

Through a United States Environmental Protection Agency Region 8 Wetland Program Development Grant, a high-resolution land cover dataset, with a primary emphasis on mapping and quantifying impervious surfaces, was developed for three watershed sub-basins in northern Utah – Lower Bear-Malad, Lower Weber, and Jordan – to support integrated water resources planning and management. This high-resolution land cover dataset can serve as an indicator of cumulative stress from urbanization; it can support the development of ecologically relevant metrics that can be integrated into watershed health and wetland condition assessments; it can provide general assessments of watershed condition; and it can support the identification of sites in need of restoration and protection.

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LIST OF ABBREVIATIONS

AGRC	Automated Geographic Reference Center
ARDA	Agricultural Rehabilitation and Development Administration
BLM	Bureau of Land Management
CLI	Canada Land Inventory
CGIS	Canada Geographic Information System
CRSP	Colorado River Storage Project
CUP	Central Utah Project
CUPCA	Central Utah Project Completion Act
CUWCD	Central Utah Water Conservancy District
FIARBC	Federal Interagency River Basin Committee
GIS	Geographic information systems
GPS	Global positioning system
GSLPP	Great Salt Lake Planning Project
HSI	Hue-Saturation-Intensity
HUC	Hydrologic unit code
ICM	Impervious Cover Model
IWRM	Integrated water resources management
LiDAR	Light detection and ranging
LULC	Land use land cover
NAD	North American Datum
NAIP	National Agriculture Imagery Program
NDVI	Normalized difference vegetation index
NED	National Elevation Dataset
NEPA	National Environmental Policy Act
NIR	Near infrared
NIRA	National Industrial Recovery Act
NPS	Nonpoint Source
OBIA	Object-based image analysis
RPA	Regional Plan Association
RPAA	Regional Planning Association of America
SWPCC	State Water Plan Coordinating Committee
TVA	Tennessee Valley Authority
UBWPC	Utah Bureau of Water Pollution Control
UDEQ	Utah Department of Environmental Quality
UDFFSL	Utah Division of Forestry, Fire and State Lands
UDNR	Utah Department of Natural Resources
UDWaR	Utah Division of Water Resources
UDWR	Utah Division of Wildlife Resources
UDWQ	Utah Department of Water Quality
UGS	Utah Geological Survey
URMCC	Utah Reclamation Mitigation and Conservation Commission
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation

USGS	United Stated Geological Survey
USRS	United States Reclamation Service
USEPA	United States Environmental Protection Agency
USFWS	United States Fish and Wildlife Service
UTM	Universal Transverse Mercator
UWPCA	Utah Water Pollution Control Act
UWPCC	Utah Water Pollution Control Committee
UWPB	Utah Water and Power Board
UWSC	Utah Water Storage Commission
WBD	Watershed Boundary Dataset
WMA	Wildlife Management Area
WPP	Wetland Program Plan
WRLU	Water Related Land Use

CHAPTER 1

INTRODUCTION

Planning is a dynamic and future-oriented activity concerned with the design, organization, and regulation of human and natural environments. It is a widely accepted way to address the problems associated with increasing human populations and growing social and environmental challenges. Generally, planning aims to improve the social, economic, aesthetic, environmental, and ecological conditions through a series of administrative activities, such as with the implementation of master plans or resource management plans or through the enactment of legislation, policies, and regulatory standards (Alexander, 2013; Al Haddad, 2011; Jhawar et al., 2012; Nedovic, 1999). Historic and traditional planning efforts have largely focused on a limited number of issues within specific political jurisdictions or sectors and they have routinely been conducted on a piecemeal basis. While these efforts may have been successful in improving some of the conditions within the realms of cities, counties, or other political jurisdictions, they frequently have not addressed the increasing and interconnected environmental and ecological issues that span regional scales (Barnes et al., 2001).

Unprecedented rates of population and urban growth have been accompanied by high degrees of land consumption and fragmentation, significant depletion and degradation of natural and biological resources, and increasing social and economic disparity (Burchell et al., 2000; Williams, 2000). These effects necessitate integrated planning approaches that transcend multiple political jurisdictions and evaluate the interconnections between biophysical resources, ecological processes, and sociocultural components and perspectives. Integrated planning approaches, such as bioregional planning and integrated water resources management (IWRM), offer more holistic approaches to land-use and resource planning and management and they provide some of the most pragmatic solutions to the ever-growing environmental issues. These planning approaches and disciplines contribute to the long-term sustainability of regions by encompassing multiple facets; they strengthen traditional planning frameworks by embracing the knowledge from numerous disciplines; and they support collaboration, stakeholder participation, and bottom-up involvement to achieve optimal outcomes.

The advancement of integrated planning approaches has largely been attributed to improvements and the increasing availability of geospatial technologies. Geospatial technologies include a variety of advanced tools, such as geographic information systems (GIS), remote sensing, global positioning systems (GPS), and surveying. These tools permit the collection, storage, mapping, manipulation, and analysis of geographic data (Aina, 2012; Pun-Cheng, 2001; Bowman, 2015). Geospatial technologies have a diverse range of applications in numerous disciplines and industries, such as forestry, range management, environmental conservation, water resources management, and urban and regional planning. They can link various scientific disciplines, both physical and social (Aina, 2012; Dekolo & Oguwaye, 2005). Therefore, geospatial technologies serve as important analytical, visual, decision-making, and planning support systems (Williams, 1999). Geospatial technologies have increasingly provided planners from a range of fields with effective tools that facilitate informed and up-to-date decisions in dynamic and multi-dimensional environments (Esri, 2011).

Geospatial technologies provide several innovative and economical functions and benefits to the various fields of integrated planning. GIS can manage and store large quantities of spatial and georeferenced data, thereby providing the ability to update, automate, integrate, and evaluate multiple datasets (Dai et al., 2001). Geospatial technologies can be used to create inventories of land use, natural resources, and historical and cultural resources, which are frequently used in characterizing landscapes and prioritizing conservation efforts (Nedovic, 1999; Civco et al., 2000). Geospatial technologies provide powerful analytical and modeling tools for addressing planning issues, determining the impacts of particular plans, selecting appropriate plans, and facilitating the implementation of projects and plans (Williams, 1999). GIS support more effective mapping, improved map currency, increased map accessibility, and enhanced map display for visualization and communication purposes (Yeh, 1999; Aksoylu & Uyguçgil, 2005). Lastly, geospatial technologies support and improve the stakeholder involvement, citizen participation, and decision-making aspects of planning processes by providing increased accessibility to current digital data and plans; by facilitating coordination between and among stakeholders and citizens; and by assisting the development and analysis of planning options or scenarios (Al Haddad, 2011; Budic, 1994).

Research Objectives

The research objectives of this thesis are: (1) to provide a synthesis of the origins, history, evolution, and fundamental principles of some key integrated planning and management approaches, including bioregional planning and IWRM; (2) to investigate the history and progression of water resources planning and management in the state of Utah, with an emphasis being placed on the development and implementation of integrated approaches and plans, such as Utah's Watershed Approach to managing nonpoint source pollution and Utah's Wetland Program Plan (WPP); and (3) to develop a high-resolution land cover dataset, with a focus on mapping and quantifying impervious surfaces, for three watershed sub-basins in northern Utah for the purpose of supporting integrated planning and management efforts.

Chapter 2 corresponds to the first objective and includes discussions about (1) the primary tenets of integrated planning and management frameworks, (2) the historical foundations of integrated planning and management approaches, and (3) the origins, evolution, and principles of bioregional planning and integrated approaches to water resources planning and management. Chapter 3 corresponds to the second objective and provides detailed examinations of (1) the history and progression of water resources management in Utah, (2) the principal legislation, policies, and programs that dictate and guide water resources planning and management in Utah, and (3) the leading programs, approaches, and plans that support integrated planning and management in Utah. Chapter 4 corresponds to the third objective and outlines (1) the objectives and requirements of a United States Environmental Protection Agency (USEPA) Wetland Program Development Grant, (2) the methods that were established and implemented to develop a high-resolution land cover dataset, and (3) the model results, watershed-scale land cover quantifications, and assessments of watershed condition based on peer-reviewed research and values.

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CHAPTER 2

TOWARD INTEGRATED PLANNING AND MANAGEMENT: ORIGINS, PRINCIPLES, AND PARADIGMS

Introduction

Integrated planning and management approaches have emerged out of the need to resolve the wide range of complex and interconnected issues that are associated with unprecedented rates of population and urban growth, high degrees of land consumption and fragmentation, substantial degradation and deterioration of natural and biological resources, and rising social and economic disparity (Bellamy and Johnson 2000; Burchell, Listokin, and Galley 2000). Integrated approaches to planning and management provide more adaptive, comprehensive, and coordinated frameworks for planning and decision-making in which the broadest range of short- and long-term development and conservation objectives are balanced and achieved (Lein 2003; Carlson and Stelfox 2009). These frameworks aim to conserve biophysical resources and maintain ecosystem processes while meeting the socioeconomic, political, and cultural requirements of current and future generations (Grumbine, 1994). Within recent decades, a number of integrated planning and management approaches have been conceived, such as integrated regional development planning, ecosystem management, integrated environmental management, integrated resource management, bioregional planning, and integrated water resources management (IWRM).

While these integrated approaches may have different objectives, the frameworks are largely similar and encompass several common themes. First, broad-scale geographic regions that span multiple jurisdictions, such as watersheds, ecoregions, or bioregions, are used as the focal units of analysis. Second, long-term perspectives are adopted to ensure the sustainability of natural resources and the maintenance of environmental processes. Third, these approaches are inclusive and support the evaluation of a broad spectrum of ecological, social, cultural, political, and economic factors. Fourth, the interconnections of these factors are assessed as a means to understand the complexity of and to develop practical and balanced solutions to environmental and socioeconomic problems. Lastly, collaboration, stakeholder involvement, participatory decision-making, and bottom-up involvement are implemented to identify common goals, to resolve conflicts, to foster shared understandings, and to develop proactive solutions (Carlson and Stelfox 2009; Margerum 1997; Bellamy and Johnson 2000) (Figure 2-1).

The varied integrated planning and management approaches have fundamentally evolved from more holistic planning theories and practices dating back to the first half of the twentieth century. Early regional planning proponents and practitioners recognized that traditional sectoral planning had shortcomings and that planning efforts should be conducted at large scales for the purpose of resolving social and economic issues and enhancing natural systems (Wheeler 2002). Regional perspectives to planning were transformed during the Great Depression, as the socioeconomic crises encouraged regional economics and regional river basin planning. The technocentric approaches associated with regional river basin planning spurred environmental awareness and the development of innovative and more holistic approaches to planning. Regional ecological planning and bioregionalism were conceived during the environmental movement. These two philosophies, which were founded on the ideals of early regional planning, emphasized the use of natural regions to maintain ecological integrity, social equality, cultural preservation, and economic stability. With the rise of environmental activism and the growing recognition of the consequences associated with massive regional river development projects, renewed approaches to water resources management were formulated. In the United States, the United States Environmental Protection Agency (USEPA) founded the Watershed Approach to improve the health of aquatic ecosystems and to coordinate interagency planning efforts. Globally, IWRM was introduced as a holistic framework for river basin management to encourage long-term sustainability.

Regional Planning

The Origins of Regional Planning

The concept of regional planning in the United States emerged in the 1920s as individuals began to apply new understandings of natural systems to the dramatically expanding metropolitan landscapes (Wheeler 2002). Regional perspectives to planning were acknowledged as local planning efforts neglected to address issues that transcended individual jurisdictional boundaries. Two general groups of regional planners, both proposing the ideal of a rationally planned regional city, were established. The first group, often referred to as the regionalists, included a small group of intellectuals led by architect Clarence Stein, sociologist Lewis Mumford, and conservationist Benton MacKaye. The regionalists founded the

Regional Planning Association of America (RPAA) in 1923. They advocated that the region should become the primary focus for American planning and they became recognized as a key entity that supported urban development that balanced nature and human beings (Fishman 2001; Roberts 1994). The RPAA defined the region as a large geographic area characterized by a certain unity of climate, soil, vegetation, industry, and culture (Talen, 2008). They further defined regional planning as the "comprehensive ordering of the natural resources of a community, its material equipment and its population for the purpose of laying a sound physical basis for the good life" (Mackaye, 1940). The second group of regional planners, often referred to as the metropolitanists, was led by Thomas Adams, first planning director of the Regional Plan Association (RPA) and proponent of the 1929 Regional Plan of New York and Its Environs (Meyers 1998). The RPA, founded in 1922 by prominent professionals and civic leaders, sought to revitalize regions through the redevelopment of core cities. Specifically, the RPA launched an ambitious effort to survey, analyze, and plan the future growth of the metropolitan region of New York (RPA 2016). The RPA developed a pragmatic approach to planning metropolitan regions by examining quantitative data about demographics, population distribution, economic conditions, land utilization, transportation, natural features, and other characteristics of the region (Wheeler 2000; RPA 2009).

Two Approaches to Regional Planning

Both the RPAA and RPA adopted more inclusive approaches to planning that were intended to remedy the social, environmental, and economic issues associated with congested industrial cities and the peripheral spread of urban development

(Talen 2008). However, while the two groups of regional planners had similar objectives, their approaches were vastly different (Meyers 1998). The RPAA promoted patterns of development that encouraged harmonious relationships between human beings and nature (Friedmann and Weaver 1979). The leaders of the RPAA believed that this would be primarily achieved through the decentralization of population and industry (Meyers 1998). The population would be channeled into a large urban region characterized by a series of towns bordered and contained by preserved open space (Figure 2-2). This proposed pattern of development was viewed as a more balanced form of regional development that would support the attainment of social equity, efficiency, and beauty (Parsons 1994; Larsen 2005; Fishman 2001). Conversely, Thomas Adams and the RPA promoted diffuse recentralization in which the primacy of central cities and their economies was reinforced and sustained (Seltzer and Carbonell 2011). The revitalized city would have the highest concentrations of people, wealth, and activity, but it would be surrounded and strengthened by suburbs and preserved natural areas (Talen 2008).

The RPAA and the RPA had a significant impact of the central ideas of city and regional planning, regional settlement frameworks, large-scale community design, open space preservation, and environmental planning. The Radburn Plan, conceptualized by the RPAA, facilitated the partial development of a planned community spanning over 150 acres in northern New Jersey in 1929. Although it lacked its own localized economic production and is often criticized as becoming a dormitory suburb, it influenced regional thinking and the design of several new

American towns and planned unit developments (Parsons, 1994). The 1929 Regional Plan of New York and Its Environs, compiled by the RPA, represented the world's first comprehensive long-range metropolitan plan. It presented a new way of thinking about regional development and governance in which vibrant, livable, and efficient communities were created and it shaped the form of twentieth century metropolitan regions by proposing new patterns of metropolitan development (RPA 2009).

Shifts in Regional Planning

The regional planning movement experienced a considerable change in the 1930s as a result of the Great Depression (Birch 1980). The economic crisis, as well as the enactment of the New Deal, triggered an upsurge in regional planning and regional economics (Higgins 1966). The field of regional planning, which had previously been characterized by a struggling profession and abstract scientific discussion, became a national priority as New Deal programs were implemented (Auger 1936). At local scales, New Deal programs were aimed at developing new towns, constructing public housing, and clearing slums (Birch 1980). However, at regional and national scales, New Deal programs were established that would regionalize policy and promote the comprehensive planning and development of river basin regions (Roberts 1994). One of the most prominent outcomes of the New Deal that reflected this regional perspective was the establishment of the Tennessee Valley Authority (TVA).

The Tennessee Valley Authority Act, signed by President Franklin Roosevelt in 1933, created the TVA and designated it as a federal corporate agency. The Act authorized the United States government to finance, plan, and execute the revitalization and development of the depleted and depressed Tennessee River Basin, an area encompassing 106,000 square kilometers (41,000 square miles) and spanning 125 counties from seven states (Black 2000; Martin 1957). From its foundation until roughly 1936, the TVA made progress in providing flood control, generating and distributing hydroelectric power, improving navigation, extending the distribution of agricultural and industrial development, countering soil erosion, providing education and welfare, reducing malaria, and elevating the general standard of living in the region. While the TVA generated significant controversy, it represented a practical example of comprehensive regional planning in which federal agencies, state governments, private developers, and public entities cooperated to manage natural resources and improve the socioeconomic conditions within a region (Boyce 2004; Barrow 1998).

Although regional planning became a matter of national priority during the Great Depression, it receded in importance during World War II. The war created a shift in which a national economy took precedence over regional, state, and local markets and endeavors (Friedmann and Weaver 1979). In fact, from the start of World War II in 1939 and up until the 1960s, regional planning interests were largely overlooked because international conflicts and industrial and technological developments were often regarded as more imperative (Daniels 2009).

During this post-war period, a new form of urban growth, characterized by mass suburbanization, had gained prominence (Auch, Acevedo, and Taylor 2006). Also, the construction of the federal highway system had been initiated (Ellis 2001) and considerable technological advances were being made (Ruckelshaus 1985). Loans provided by the Federal Housing Administration and the Veterans Administration assisted Americans in purchasing an estimated 11 million new homes and the Interstate and Defense Highway Act facilitated suburban sprawl by expanding infrastructure and reducing the cost of travel. These activities rapidly transformed the landscape and regularly contributed to environmental degradation, social inequality, and unnecessary economic costs (Williams 2000). An increasing awareness of these impacts, which was amplified by the release of Rachel Carson's influential environmental book entitled *Silent Spring* in 1962, contributed to the rise of environmental activism and the development of more progressive approaches to planning, namely regional ecological planning and bioregional planning (Daniels 2009; Lang 2002).

Regional Ecological Planning and Bioregional Planning

The Foundations of Regional Ecological Planning

Regional ecological planning is a process in which the interrelationships of sociocultural and biophysical features within a naturally-defined landscape are evaluated for the purpose of providing potential future options that balance human actions and the integrity of natural processes (Ndubisi 2002; Steiner, Young, and Zube 1988). Regional ecological planning practices began to surface in 1960s. However, the fundamental tenets of regional ecological planning stem from the philosophies promoted by the members of the RPAA. The RPAA reconsidered cities in relation to regions, aimed to conserve natural resources, argued that maintaining and enhancing natural systems were vitally important, and advocated the need for designs that were guided by the interactions between people and their biophysical environments (Daniels 2009; Ndubisi 2002).

Development of Systematic and Technical Approaches

The practice of regional ecological planning began to mature when systematic and technical approaches were established. While several people can be credited for this progression, there are certain individuals who made significant contributions. Ian McHarg, Philip Lewis, George Angus Hills, Roger Tomlinson, and Howard Fisher contributed to the growth of planning theories, practices, and applications through the development of innovative processes and techniques that facilitated the assessment of spatial relationships.

Ian McHarg, a Scottish landscape architect, and his colleagues at the University of Pennsylvania developed a systematic approach to ecological planning that stressed the equal importance of environmental, social, and economic concerns (Steiner 2011). Through this approach, McHarg acknowledged that humans should be accepted as an integral part of ecology and that ecology should be accepted as part of planning (Ndubisi 2002). McHarg applied and popularized the use of the overlay technique, a method developed in the 1880s by landscape architect Charles Eliot in which a series of maps could be layered on top of each other to understand and classify regional landscapes (Daniels 2009; Steiner 2008; Ndubisi 2002).

By incorporating data from several scientific disciplines, McHarg would inventory and evaluate sociocultural and biophysical resources, analyze spatial relationships and patterns, assess landscapes for development potential and environmental constraints, and identify suitable locations for future land uses (Thayer 2003; Collins, Steiner, and Rushman 2001; Daniels 2009). This information, when combined with the needs and desires of the population of the region, would support the development of alternative future scenarios (McHarg 1981). This systematic ecological approach, which is commonly referred to as land suitability analysis, was detailed in McHarg's 1969 publication of *Design with Nature*, a book that became profoundly influential in the fields of landscape architecture and regional and environmental planning (Thayer 2003).

Along with Ian McHarg, Philip Lewis and George Angus Hills are credited with the development and progression of the map overlay technique and natural resource inventory process as critical elements of the regional design process (UWM, 2017). Philip Lewis, a professor of landscape architecture at the University of Wisconsin, became nationally recognized for his work in cataloging ecologically vital landscape features at regional scales. During the early 1960s, he devised a mapping technique for identifying significant natural and cultural resources in Wisconsin. During this process, he and his colleagues documented that the majority of these resources were concentrated along corridors, especially near rivers and within major drainage areas. Philip Lewis referred to these areas as environmental corridors (Fábos 2004). The concept of environmental corridors became a fundamental element of landscape conservation and ecological sustainability (Murrell 2003). Philip Lewis was the first in his field to shape a landscape plan around environmental corridors when he developed the Wisconsin Heritage Trails

Proposal of 1964, the first major statewide greenway system plan that would protect environmentally sensitive areas (Steinitz 2008; Fábos 2004).

George Angus Hills, Canadian forester and chief research scientist with the Ontario Department of Lands and Forest, made significant contributions to ecological inventories and landscape classification systems. George Angus Hills developed a physiographic-unit approach to landscape analysis in 1961, known as the Hills System of Land Classification. This system divided regions into smaller units of physiographic similarity based on climate and landform. The smaller units were compared with a predetermined set of land use categories and ranked by potential or limitation of each land use. The land use category with the highest feasibility ranking was recommended as a major use (McHarg and Steiner 1998). This system combined ecological principles with the science, technology, and arts of forestry and agriculture, as well as other types of land management in order to provide a foundation for resource management and regional land use plans (Jacobs, 1979). In 1961, a document entitled *The Ecological Basis of Land Use Planning* was published that detailed this approach.

During the same year, the Government of Canada launched the Canada Land Inventory program under the Agricultural Rehabilitation and Development Act of 1961 (Jacobs, 1979). The Canada Land Inventory was established to inventory present land use; to assess the capability of land for agriculture, forestry, wildlife, and recreation; and to evaluate social and economic factors relative to land use (ARDA 1965; Tomlinson 2012). Roger Tomlinson, a visionary geographer from England, convinced the director of the Canada Land Inventory that computers could be used to automate this inventory process. Subsequently, Tomlinson conceived a digital process for overlaying and analyzing geographic features when he developed the first computerized GIS. Tomlinson designed, developed, and implemented the Canada Geographic Information System (CGIS) in 1967 to support a comprehensive land resource survey program for Canada (Tomlinson 1967; Malczewski 2004). With the development of the CGIS, Tomlinson pioneered the use of GIS in large-scale applications for environmental management and regional planning (Tomlinson 1968; Dekolo and Oguwaye 2005).

In the United States, Howard Fisher, an architect from Chicago, Illinois, founded the Laboratory for Computer Graphics at the Harvard Graduate School of Design in 1965. Fisher became interested in developing a computer mapping system that would support and improve planning activities by aggregating and analyzing ecological, sociological, and demographic data (Crisman 2006; Waldheim 2011). Fisher worked with a programmer, Betty Benson, to create the Synagraphic Mapping System (SYMAP), the first automated computer mapping system that included spatial-analytic capabilities (Steinitz 2013). Fisher was joined by William Warntz, a professor of theoretical geography, who eventually directed the research of the Laboratory toward spatial analysis. During the 1970s, the Laboratory developed additional cutting-edge computer-based mapping programs, such as GRID, IMGRID, and ODYSSEY. These programs enabled more comprehensive, systematic, and efficient land suitability analyses and provided the technical frameworks for contemporary geospatial software programs (Crisman 2006; Collins, Steiner, and Rushman 2001; Malczewski, 2004).

Emergence of Bioregionalism

As the field of regional ecological planning was gaining scientific credibility and making technological strides, the philosophy of bioregionalism emerged as part of a series of interrelated social and environmental movements (Aberley 1999; Lang 2002). The term bioregionalism appears to have been conceived by Allen Van Newkirk, a political activist from Canada, in 1974 when he published a research prospectus entitled *Bioregions: Towards Bioregional Strategy for Human Cultures* (Alexander 2003). Van Newkirk also founded the Institute for Bioregional Research in Nova Scotia to begin mapping bioregions as a basis for conservation (Glotfelty and Quesnel 2015). According to Van Newkirk, bioregionalism was a practice in which human populations within bioregions would "aid in the conservation and restoration of wild eco-systems" and "discover regional models for new and relatively non-arbitrary scales of human activity in relation to the biological realities of the natural landscape" (Aberley 1999).

In 1978, the concept of bioregionalism was expanded upon by Peter Berg, environmental writer and activist, and Raymond Dasmann, conservation biologist, in San Francisco, California. Berg established the Planet Drum Foundation to promote bioregionalism, sustainable planning practices, and grassroots approaches. Dasmann, who had been working with Miklos Udvardy of Sacramento State University to catalog biogeographic provinces, promoted the concept of bioregionalism through his academic research. The map of biogeographic provinces produced by Udvardy (Figure 2-3) formed the basis of bioregionalism (Dasmann 1976; Carr, 2004). Berg and Dasmann collectively defined a bioregion as a "geographic area having common characteristics of soil, watershed, climate, native plants, and animals." Furthermore, they stated that a bioregion refers to "a geographical terrain and a terrain of consciousness – to a place and the ideas that have developed about how to live in that place" (Lang 2002; Berg 1991).

In 1981, Jim Dodge, a novelist and poet, added to the philosophy of bioregionalism and stated that "a central element of bioregionalism – and one that distinguishes it from similar politics of place – is the importance given to natural systems" (Dodge 1981). In 1985, Kirkpatrick Sale summarized the concept and stated that a bioregion is a "place defined by its life forms, its topography and its biota, rather than by human dictates; a region governed by nature, not legislature" (Sale 1985).

<u>The Field of Bioregional Planning</u>

The philosophy of bioregionalism and McHarg's ecological approach to planning coalesced to form the field of bioregional planning. The concept of bioregional planning was introduced in the early 1980s when bioregional thinkers George Tukel and John Todd began to overlay patterns of human settlement, termed artificial terrain maps, on top of patterns of natural succession, termed biological maps, in order to plan urban settlements that would contribute to the maintenance of the ecological stability of a bioregion. In 1982, Tukel broadened the discussion on bioregional planning in a publication entitled *Toward a Bioregional Model: Clearing Ground for Watershed Planning*. In this publication, Tukel suggested that the key to a bioregional model of planning was in maintaining and restoring the health and diversity of a bioregion and in connecting human movements to ecological stress.

This approach would allow for incremental change as part of a long-term comprehensive vision while being in accord with the natural patterns and processes (Carr 2004).

The notion of bioregional planning gained some prominence in the 1990s when it was realized that previous approaches to planning, which were often directed by singular governmental entities, were not succeeding in balancing environmental conservation and socioeconomic concerns (Mason 2011; Thayer 2003; Sportza 1999). Natural resource managers, environmental interest groups and policy makers, and some governmental agencies and politicians began to show an increasing interest in collaborative, multi-disciplinary, and more holistic approaches to landscape planning and management (Brunckhorst 2000; Aberley 1999).

Accordingly, researchers and practitioners within the discipline and field of bioregional planning began to refine the key tenets and concepts of bioregional planning and develop practical frameworks that unified both natural and cultural systems. In 1993, Douglas Aberley, a bioregional planner, published a book entitled *Boundaries of Home: Mapping for Local Empowerment*. In this book, Aberley outlined a systematic approach for mapping the biophysical and cultural features within bioregions. He affirmed that mapping was an integral component of building community and for showing a vision for a sustainable future (Aberley 1993). In 1996, Kenton Miller, a forestry economist and leader in natural resource conservation, provided updated, and now widely accepted, definitions for the terms bioregion and bioregional planning. He defined a bioregion as “a geographic space that contains one whole or several nested ecosystems, characterized by its landforms, vegetative cover, human culture, and history, as identified by local communities, government agencies, and scientists." He proceeded to define bioregional planning as "an organizational process that enables people to work together, acquire information, think carefully about the potential and problems of their region, set goals and objectives, define activities, implement projects, take actions agreed upon by the community, evaluate progress, and refine their approach" (Miller 1996).

Key Elements of Bioregional Planning

The research conducted by these innovative scientists and planners collectively provided a solid foundation for contemporary bioregional planning. There are several key elements of contemporary bioregional planning. First, an emphasis is placed on natural, rather than administrative, regions, such as watersheds, ecoregions, or bioregions. These regions are generally characterized by ecological or biophysical systems, social and cultural traditions, and economic or political conditions (Tonn, English, and Turner 2006; Matysek 2004; Seltzer and Carbonell 2011). Second, since natural geographic regions are the focal units of analysis in bioregional planning, inter-jurisdictional decision-making is encouraged (Matysek 2004). Third, sustainable development is promoted by recognizing the relationships between, and giving practical effect to, environmental integrity, human well-being, cultural values, and economic efficiency (OPNC 2012; Ontario Nature 2014). Fourth, people, towns, and cities are recognized as functioning elements of ecosystems (Matysek 2004). Fifth, the preservation of biodiversity, natural resources, and ecological processes is fostered (Boothby 2000; Sportza 1999). Sixth, more flexible and interdisciplinary frameworks that promote collaboration and creative thinking are employed (Donovan et al. 2009; Loheed, Howard-McHuh, and Stein 2011). Lastly, bottom-up approaches that support participatory decision-making and underline stakeholder views and values are utilized (Aberley 1999; Donovan et al. 2009).

Challenges and Benefits of Bioregional Planning

The implementation of bioregional planning presents immense political, institutional, and social challenges due to the geographic scale and complexity of issues, as well as due to the limited number of established planning paradigms and methods. Identifying appropriate scales and boundaries becomes problematic because naturally-defined systems have generally not been accepted in political realms, and existing agencies may be legally bound to restrict their scope of activity and limit expenditures on specific jurisdictions. At larger scales, inter-agency cooperation and information flow may be constrained because local, county, or state institutional arrangements and objectives may not be in accord and may not facilitate collaboration. Stakeholder involvement provides an added dimension of complexity because differing perspectives and beliefs can instigate conflict, particularly in locations where environmental education resources are limited (Lambert et al. 1995; Miller 1996).

Although the implementation of bioregional planning presents challenges, there are numerous social and ecological benefits. The process of bioregional planning is inherently community based. Therefore, residents, stakeholders, and management agencies have greater influence over policies and legislation, have improved access to information, and stand to gain a better awareness of the linkages and interdependencies among the resources within their region (Miller 1996; Brunkhorst 2001). Community involvement also supports the development of a model that reflects the collective vision of a region in which the character and social and economic well-being of individuals and communities are protected (Swinnerton 2009). Bioregional planning also enables agencies and communities to manage vital ecosystem attributes and functions in such a way that biodiversity, clean air and water, healthy soils, flood protection, balanced agricultural production, and landscape and visual amenity are supported and enhanced (Brunkhorst 2001). These benefits are evidenced by the number of bioregional plans that are emerging in various countries throughout the world. In Australia, New Zealand, and South Africa, bioregional planning has been implemented by government agencies and has played an integral role in conserving biodiversity, maintaining ecosystem function, and creating biosphere reserves (Miller 1996; Brunkhorst 2001; Purves and Holmes 2012; DCMF 2011).

Watershed Planning and Management

<u>Origins of Water Resources Planning and Management</u>

Since the early 1800s, federal, state, and local governments in the United States have conceived and implemented plans to develop and manage water resources (Loucks 1998). However, the notion of planning at a watershed or river basin scale did not emerge until the late nineteenth century (Molle et al. 2007). One of the most notable events relating to the history of watershed planning and management occurred in 1878 when John Wesley Powell, ethnographer, explorer, and future director of the United States Geological Survey, transmitted a report to the Secretary of the Interior. This report was published in 1879 as the *Report on the Lands of the Arid Region of the United States*. In this publication, Powell recommended that the arid West be organized into hydrographic drainage districts (Figure 2-4), rather than townships and sections, for the purpose of human settlement and governance (Gelt 1998; Molle 2006; Powell 1879). Powell argued that lands should be surveyed and classified based on potential land use prior to being released to settlers. His plan called for the coordinated development of water, land, forestry, and mineral resources (Holmes 2013). While Powell's plan was revolutionary for the time, it was quickly dismissed by the United States Government, and the stance that civilization, science, and technology should preside became the dominant ideal. Consequently, the United States Reclamation Service (now known as the United States Bureau of Reclamation), founded in 1902, began to organize a series of federally funded water management projects (Molle 2009).

Management of water resources, which continued on a piecemeal basis, primarily focused on the construction of infrastructure that would control, divert, impound, and store water (Meltz 2008; Molle 2009). The magnitude and scale of these river basin projects began to change as technological advances were achieved. Small single-purpose projects evolved into large multi-purpose projects that were focused on providing water supply, flood control, hydroelectric power, navigation, and water storage for irrigation (Molle 2007; Downs, Gregory, and Brookes 1991;

Reuss 2005). During the 1930s, massive structural projects were undertaken and river basins were viewed by water engineers and water economists as complex resource systems wherein water and other commodities could be developed for economic gain (Hooper 2003). As a result, the management of water resources shifted from local to regional and national scales, especially in the western United States where population growth and agricultural production were restricted by water supply constraints (Molle 2009; Pegram et al. 2013).

Regional River Basin Planning

The regional planning perspective that emerged during the Great Depression significantly influenced water management approaches and reinforced the concept that river basins should be managed as single units (Pegram et al. 2013). With the creation of the TVA in 1933, the Tennessee River Basin was realized as the most optimal planning unit for improving regional water development and management (Meltz 2008; Gelt 1998). Although the TVA developed the Tennessee River and its tributaries into one of the most controlled river systems in the world (Figure 2-5), and is often criticized as being a highly centralized and authoritative agency, it pioneered a shift from simple resource exploitation to more integrated planning that encompassed other aspects of development and human welfare (Figure 2-6) (Downs and Gregory 2004; Kenney 1999; Barrow 1998). The TVA is considered a success in terms of providing the first example of leveraging river basin management beyond traditional water resources management (Pegram et al. 2013).

Building upon the TVA model, President Franklin Roosevelt established the Federal Interagency River Basin Committee (FIARBC) in 1943 as a means for improving integrated planning and interagency coordination at the river basin level (Molle 2006). The FIARBC set up regional interagency committees for six river basins in the United States. The regional committees, which were often little more than advisory bodies, were frequently not able to reconcile separate agency plans and policies; therefore, they did not effectively promote integrated basin-wide programs (Holmes 1974; Barrow 1998). After decades of failed attempts to coordinate water policy, the Water Resources Planning Act was enacted in 1965 to establish a National Water Resources Council and several regional river basin commissions, called Title II River Basin Commissions (Adams, Noonan, and Newton 2000). Title II River Basin Commissions were not created in basins where water had been allocated according to Supreme Court decisions or by compacts, such as the Colorado River Basin. The Council supported the idea of improved comprehensiveness and integrated action and it was responsible for studying and assessing the adequacy of water supplies. It also provided a foundation for the planning of water resources and related natural and environmental resources (Dworsky, Allee, and North 1991). Soon after the passage of the Water Resources Planning Act, a new political philosophy emerged that criticized the traditional technocentric approaches to water management (Margerum 1995).

Renewed Approaches to Water Resources Planning and Management

The extensive water development projects that occurred during the first half of the twentieth century often resulted in environmental degradation, economic losses, social injustices, and inefficient resource use (Lee and Dinar 1995). With the rise of the environmental activism and the growing recognition of the social and ecological costs associated with massive infrastructural expansion, river basin development started to lose momentum (Molle 2007). Previous assumptions about water resources planning and management were questioned and it was recognized that engineering solutions alone were no longer adequate to address the multifaceted and interconnected problems within river basins. Consequently, the federal government retreated from traditional river basin management and began working toward a supportive, legislative role that dealt with land management, pollution abatement, species protection, and resource preservation (Pegram et al. 2013). The enactment of laws, such as the National Environmental Policy Act (NEPA) in 1969 and the reorganized Federal Water Pollution Control Act (i.e. Clean Water Act) in 1972, and the establishment of the USEPA in 1970 supported this new direction (Meltz 2008; Pegram et al. 2013).

During this era, the National Water Resources Council developed national assessments of the nation's water resources (issued in 1968 and 1978), state-level planning programs, and *Principles and Standards for Planning Water and Related Land Resources* (issued in 1973). However, in 1981, the Reagan administration dismantled the six Title II River Basin Commission with Executive Order 12319 and removed funding for the National Water Resources Council (Moreau et al. 1999).

The period from 1970 to 1985 was marked by a significant departure in water development projects, and renewed approaches to river basin planning and water resources management began to appear. Despite a limited national policy for watershed management, many states passed watershed management policy directives or legislation by the late 1980s. These new approaches focused on water resources management at basin scales; incorporated social, economic, and environmental aspects; and included stakeholder committees and participatory decision-making (Pegram et al. 2013; Margerum 1995). By the early 1990s, more inclusive approaches were being adopted, and in 1991, the USEPA developed the Watershed Protection Approach. The Watershed Protection Approach was established as an integrated management strategy to address watershed restoration and protection in a holistic manner; to create a coordinating framework for intergovernmental and interagency agreements; and to balance institutional objectives of federal, state, and local agencies. This strategy emphasized the maintenance of the physical, chemical, and biological integrity of aquatic ecosystems; the protection of human health; and the sustainability of economic growth (USEPA 1991; Graf et al. 1999).

Since 1991, the USEPA has iteratively revised, updated, and modified this integrated approach. Now referred to as the Watershed Approach, the USEPA defines it as a flexible framework for managing water resource quality and quantity within specified drainage areas, or watersheds, through management actions that are supported by sound science, appropriate technology, and stakeholder involvement (USEPA 2008). The Watershed Approach encompasses several key elements to provide guidance to state and tribal entities who are interested in developing comprehensive watershed-based plans, programs, and projects (Figure 2-7). These elements include (1) the establishment of hydrologically-defined management units that are large enough to ensure that significant threats to aquatic resources are evaluated, (2) the involvement of stakeholders to support the identification of issues, the selection of priorities, and the implementation of plans, (3) the coordination and collaboration with other agencies and partners, (4) the integration of management activities and planning efforts, (5) the identification of priority regions or locations that should be targeted for restoration activities, and (6) the development and implementation of integrated management strategies, practices, and solutions (USEPA 2008).

Collectively, these elements support the development of watershed-based programs and activities that are embedded in comprehensive state and tribal watershed plans (USEPA 1996). Comprehensive watershed plans provide a strategy for assessing and managing watersheds in a more integrated manner; support the maintenance, protection, and restoration of natural and biological resources within watersheds; enhance the quality of life in communities; and address multiple issues simultaneously. The USEPA continues to advocate the Watershed Approach and the development of comprehensive watershed plans by working with states, tribes, and watershed groups to realign programs and to strengthen support for watershed-based programs and activities (USEPA 2008).

Integrated Water Resources Management

Following the development of the Watershed Protection Approach in 1991, the principles of IWRM began to be adopted in various countries throughout the world, and in 1992, the principles of IWRM were internationally endorsed during the United Nations Earth Summit (Meltz 1991; Molle et al. 2006). The Global World Partnership defines IWRM as a "process which promotes the coordinated development and management of water, land, and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (Bach et al. 2011). IWRM is based on the understanding that water resources are an integral component of ecosystems, a vital natural resource, and a social and economic good. It consists of a holistic approach that gives due regard to economic efficiency, social equity, and environmental and ecological sustainability. Through the IWRM framework, the interrelationships of issues and demands for water are evaluated and addressed at multiple scales, from watersheds to transboundary basins. The approach emphasizes incremental continuous improvements while adhering to long-term goals and promoting long-term sustainability for the entire watershed. It is interdisciplinary and includes the human dimension through stakeholder involvement, participatory decision-making, and public education (Cobourn 1999; Molle 2007). Lastly, and most importantly, IWRM has become a globally-accepted alternative to traditional sector-based and strict top-down water management approaches that have previously dominated water resources management (Molle 2006). While IWRM is not a mainstream approach for watershed planning in the United States, it has been implemented in all or portions of California, Delaware, Florida, Minnesota, New Mexico, Oregon, and Washington. The state of Oregon has taken the lead by implementing a statewide integrated water resources strategy (Bateman and Rancier 2012).

Challenges and Benefits of Integrated Water Resources Approaches

Although the USEPA Watershed Approach and IWRM present ideal models for river basin management, there are several challenges. The primary challenge is that watershed boundaries typically do not coincide with political boundaries, which often creates issues with accountability and implementation. Existing administrative structures inhibit integrated approaches because they are sectorally organized and may contradict watershed authorities or commissions. Integrated watershed planning approaches involve great complexity and successful models require comprehensive inputs of hydrologic, ecological, social, cultural, economic, and political data. The participatory planning process is slow, dynamic, and aims to include diverse interests. Consequently, finding agreement may be arduous and demanding (Lee and Dinar 1995; Graf et al. 1999).

While the implementation of these approaches presents several challenges, numerous benefits are provided. The primary benefit of planning at a watershed or basin scale is that these units provide a more comprehensive and rational setting for resolving natural resource problems because they are biogeophysical units with a high degree of functional integrity, homogeneity, and interconnectedness, even when upper, middle, and lower sections have different conditions and human activities (Barrow 1998; Gelt 1998). Effective integrated water resources planning and management approaches can support a wide range of beneficial services, including water supply, water quality, groundwater recharge, flood control, sediment control, navigation, hydroelectric power generation, fisheries, biodiversity, habitat preservation, and recreation (Graf et al. 1999; Barrow 1998). They also support collaboration, improved management decisions, and consensus among stakeholders, thereby reducing conflicts (Lee and Dinar 1995; NVDWR 1999).

Conclusion

Integrated planning and management approaches have arisen for several reasons. First and foremost, the establishment of these approaches is related to the growing recognition of the wide range of complex and interrelated environmental issues that transcend multiple administrative boundaries. Remarkable rates of urban development and resource consumption have resulted in the fragmentation of landscapes and habitat, degradation of natural and biological resources, impairment of hydrological and aquatic ecosystems, and escalating social and economic inequality. Second, integrated approaches have emerged and progressed as environmental awareness and scientific research have promoted and provided greater understandings of ecosystem functions and services. Third, integrated approaches have been developed to address the fragmented planning, management, and decision-making that are prevalent with traditional sectoral planning. Lastly, increasing community expectations for greater involvement and higher demands for accountability and transparency have encouraged the development of integrated approaches (Margerum 1997; Bellamy and Johnson 2000).

Integrated approaches, such as bioregional planning and IWRM, provide purposeful holistic strategies for maintaining and enhancing ecological conditions, environmental sustainability, social equity, and economic efficiency. They strive to balance ecological integrity with human development and activities by recognizing the interdependencies of natural, political, and sociocultural systems (Bellamy and Johnson 2000). Large geographic areas are emphasized to ensure that ecosystem processes and biotic communities remain viable over the long-term (Miller 1996).

Bioregions and watershed basins have been identified as suitable planning and management units because they are naturally delineated systems that are generally characterized by similar hydrological, geomorphological, ecological, and sociocultural conditions (Barrow 1998). Within these units, the linkages between geographies and resources are acknowledged, and this recognition encourages holistic problem solving and reduces unintended environmental consequences (Graf et al. 1999). Integrated approaches promote collaboration and decentralization through the implementation of interdisciplinary frameworks and through inter-jurisdictional and inter-agency planning, decision-making, and management (Matysek 2004). Within integrated approaches, humans are recognized as integral functioning components through the assessment of cultural traditions, historical land use and settlement patterns, and sociopolitical factors. Additionally, the perceptions and objectives of humans are accounted for during the public participation and stakeholder involvement processes.

Integrated approaches are finding increasing applications in community planning and natural resource management. While the long-term ecological and quality of life benefits of these strategies are immense, significant challenges are present in terms of implementation. The implementation of integrated planning and management approaches may be overwhelming for agencies given the scale and complexity of issues. The asymmetry between political boundaries and naturally-defined regions can lead to legislative gaps and overlaps due to differing county and municipal regulations (Cohen and Davidson 2011). Conflicting policies may pose insurmountable barriers to effective planning and management (Lee and Dinar

1995), and existing administrative structures may not be compatible with integrated watershed authorities or regional planning commissions. Therefore, authorities and commissions may merely serve as advisory bodies (Barrow 1998). Stakeholder involvement and participatory decision-making may provide additional challenges. The diverse range of interests and opinions may delay the planning process and prove difficult in finding consensus (Graf et al. 1999). Additionally, administrative officials may be slow in relinquishing their decision-making power (Cohen and Davidson 2011).

These implementation challenges can be addressed by developing formalized and practical frameworks that provide coordinating strategies for interagency agreements and that balance the objectives of federal, state, and local agencies. These frameworks should employ both bottom-up and top-down approaches to ensure that institutional arrangements provide for intersectoral linkages and to ensure that local community needs are carefully balanced with those of society as a whole (Bach et al. 2011). These approaches should provide guidance for delineating planning and management units based on some realistic combination of hydrologic connectivity, biophysical similarity, and sociopolitical interests (Cohen and Davidson 2011; Graf et al. 1999). Integrated approaches should define feasible and attainable goals, and the achievement of these goals should be measured by incremental continuous improvements that adhere to long-term objectives and sustainability (Cobourn 1999; Graf et al. 1999). Integrated approaches should be embedded into comprehensive statewide or regional plans and programs. However, appropriate spatial scopes should be defined for successful implementation, and plans, programs, and activities should initially be implemented at more local levels where political, institutional, and funding decision-making is uniform. These frameworks should support innovative and flexible strategies for engaging a wide range of relevant stakeholders and for facilitating conflict resolution because collaboration, public participation, and consensus are fundamental components of effective and well-received plans and activities (Graf et al. 1999). Lastly, geospatial technologies, such as geographic information systems and remote sensing, should be incorporated into integrated planning and management processes to enable more rapid and efficient analyses, to support improved understanding of complex systems, and to facilitate informed decision-making.

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Figures

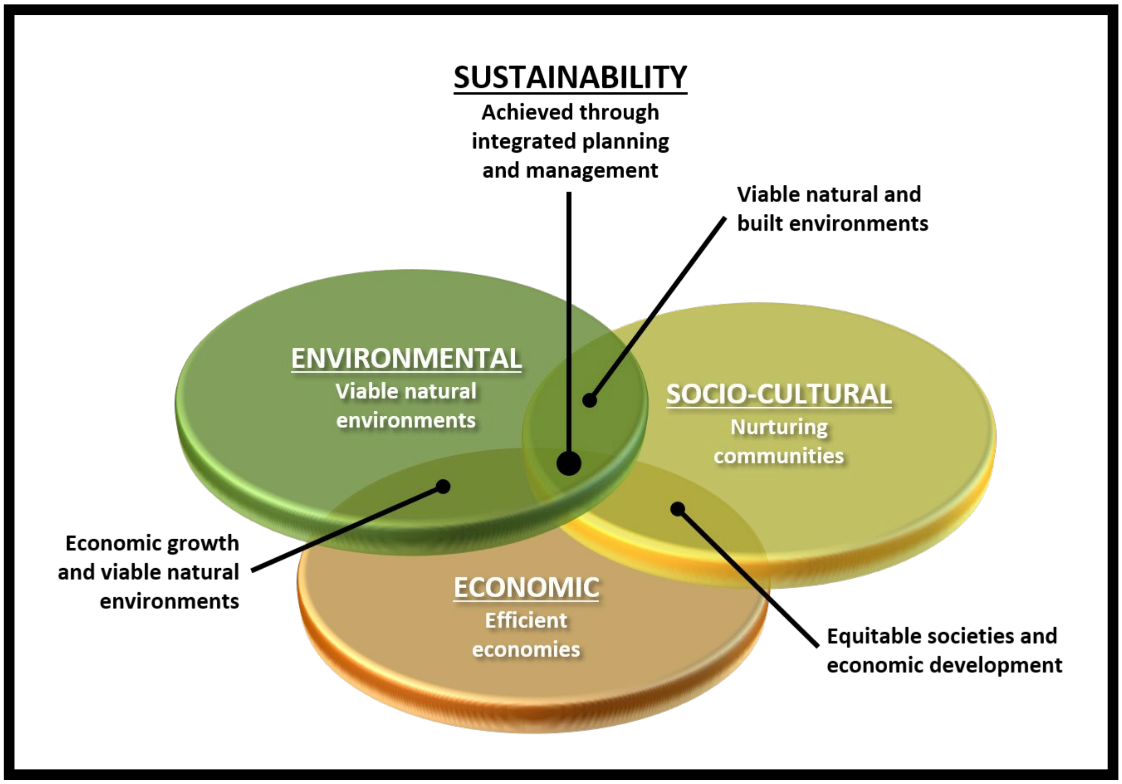

Figure 2-1. Key themes of sustainability and integrated planning and management. Adapted from: Computing for Sustainability, 2009 (https://computingforsustainability.com/2009/03/15/visualising-sustainability/).

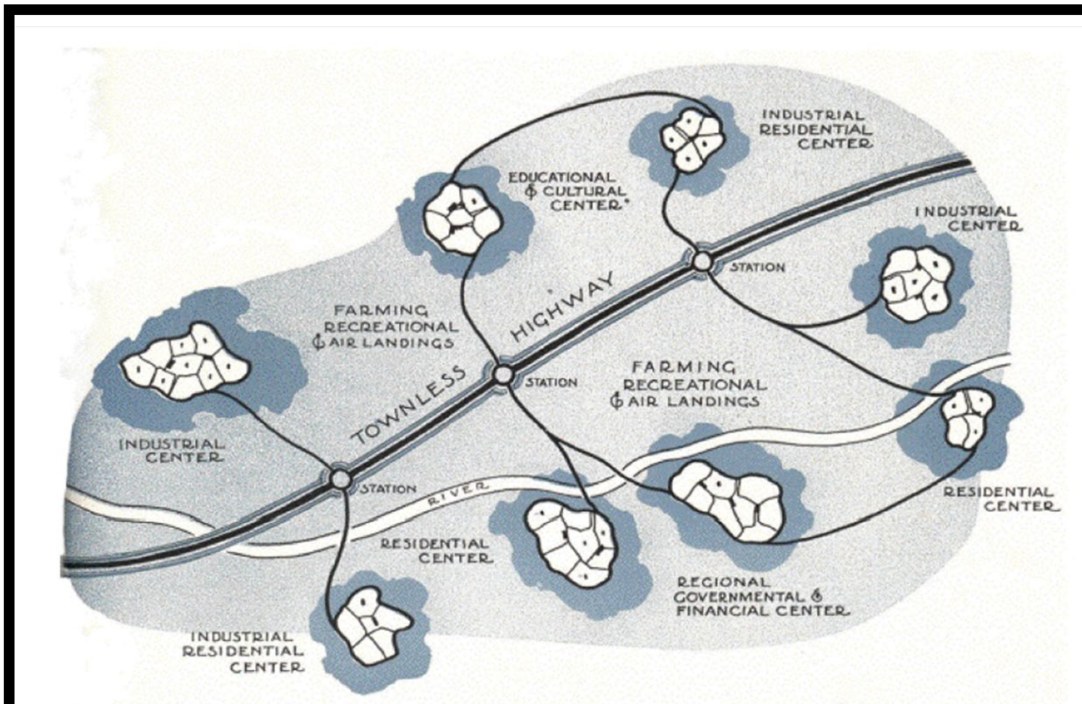

Figure 2-2. Conceptual drawing of a Regional City designed by Clarence Stein of the Regional Planning Association of America, May 1925. Source: Talen, 2008.

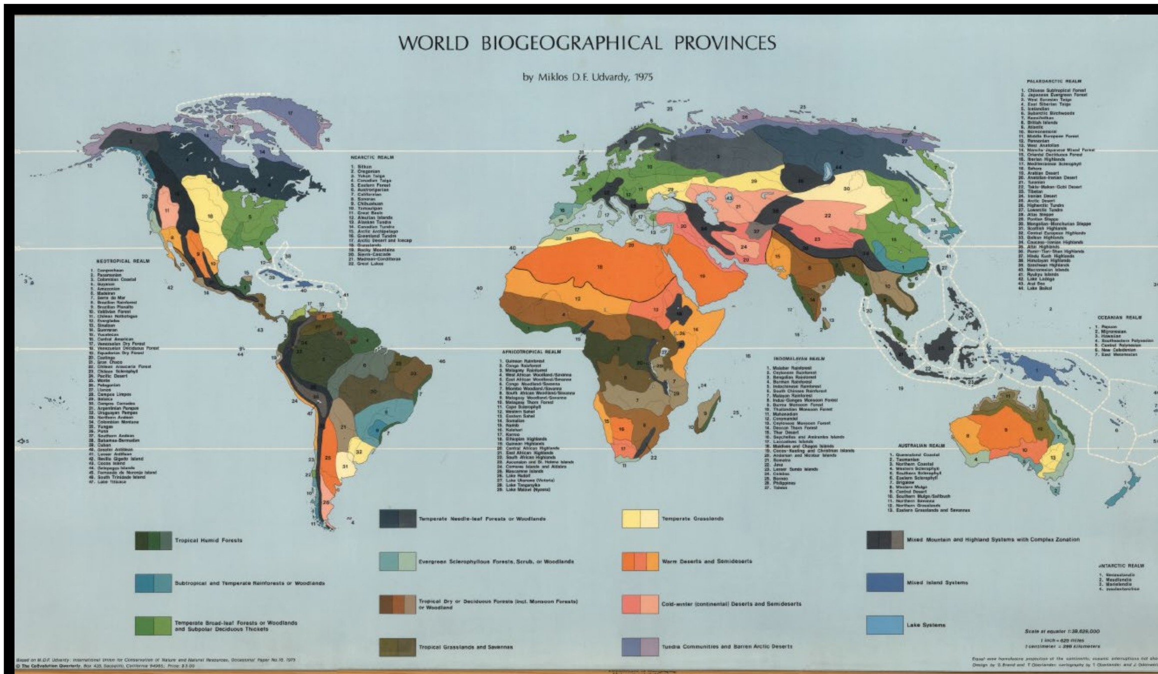

Figure 2-3. World Biogeographical Provinces by Miklos Udvardy, 1975. Source: David Rumsey Map Collection (www.davidrumsey.com).

Figure 2-4. Drainage Districts of the Arid Region by John W. Powell. Source: Powell, 1891 (*Eleventh Annual Report of the Director of the United States Geological Survey, Part 2 – Irrigation: 1889-1890*).

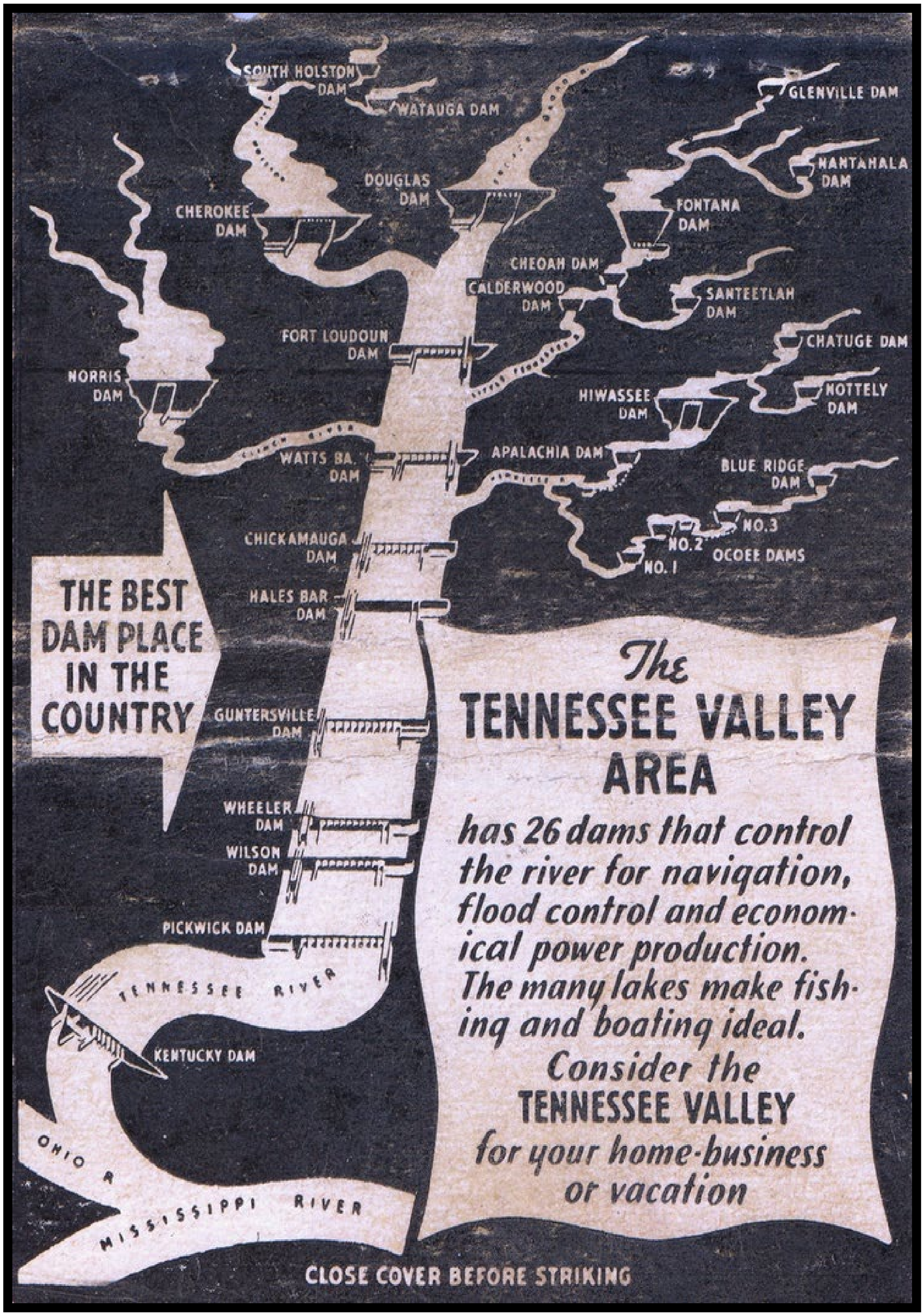

Figure 2-5. Diagram of the Tennessee Valley Area water control system, showing 26 dams that were constructed to provide flood control, generate hydroelectric power, improve navigation, to extend the distribution of agricultural development, and to elevate the general standard of living. Source: https://www.digitalcommonwealth.org/

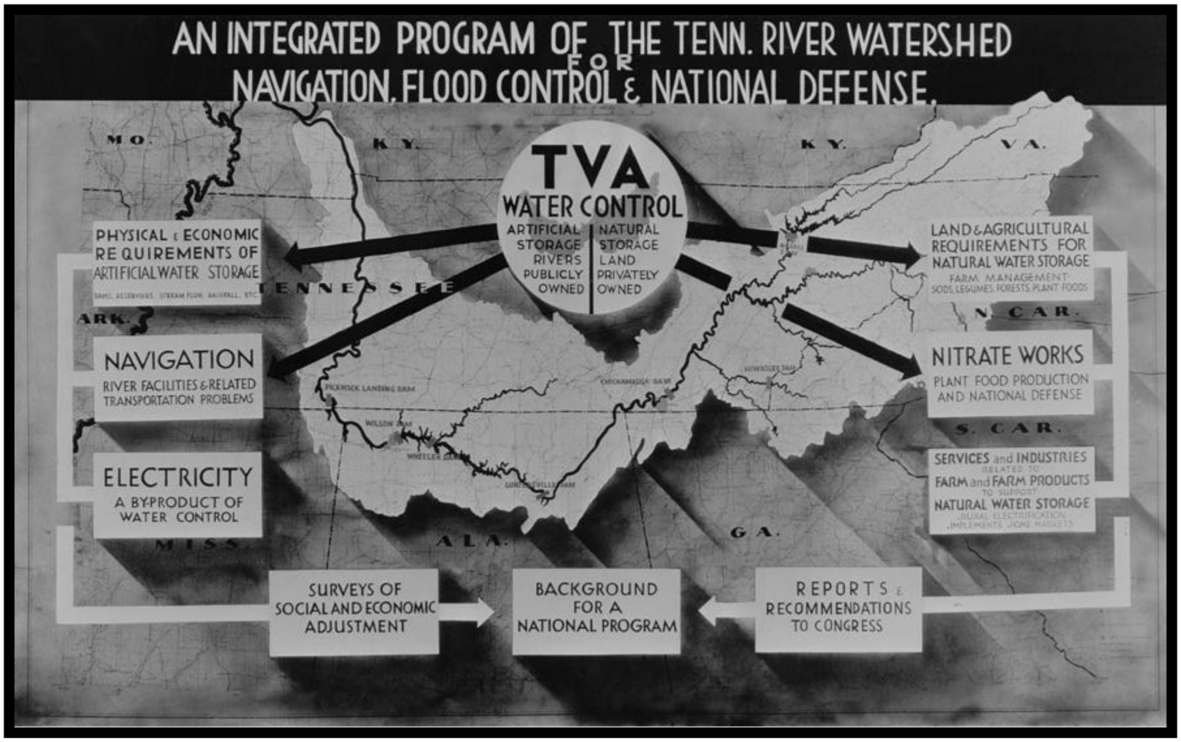

Figure 2-6. Tennessee Valley Authority's comprehensive planning chart from the New Deal era (circa 1940), mapping the benefits of constructing several hydroelectric dams to provide flood control, navigation, electricity, and nitrate fertilizer. Source: Everett Art Collection (https://fineartamerica.com/featured/tennessee-valley-authoritys-everett.html).

Figure 2-7. United States Environmental Protection Agency (EPA) Watershed Approach elements and planning process. Source: United States EPA Watershed Academy Web: Introduction to Watershed Planning (https://cfpub.epa.gov).

CHAPTER 3

WATER RESOURCES PLANNING AND MANAGEMENT IN UTAH: HISTORY, PROGRESSION, AND INTEGRATED APPROACHES

Introduction

Utah is located in the arid Intermountain West of the United States and it is ranked as the second driest state in the nation based on average annual precipitation (Fornataro, 2008). Therefore, water resources planning and management in Utah has a justifiably lengthy and eventful history and a complex organization. From the moment that settlers entered the Salt Lake Valley in 1847, water development and irrigation projects became a defining feature on the landscape, and as the population grew in Utah, water resource issues became a topic of significant controversy. The demand for and competition over water resources encouraged federal government involvement (Donaldson, 2007). During the early to mid-twentieth century, water development legislation was considerable, reclamation projects were rampant, and interstate water negotiations were common. The primary goals of water development legislation and projects were to promote farming opportunities and to secure year-round water supplies for irrigation (USBR, 2011). While these objectives were largely attained, environmental impacts and mitigation were frequently not addressed.

The lack of environmental concern, accompanied with rising social and economic costs and inadequate planning and coordination, eventually received some recognition by federal and state agencies. Although the federal government and Utah officials generally continued to support water development projects in

Utah, management perspectives gradually shifted as it was recognized that engineering solutions alone were no longer adequate in addressing the number of water resource issues. Federal agencies retreated from traditional management practices, began decreasing the funding for and number of hydrological infrastructure projects, and began regulating water resources through land management, pollution abatement, species protection, and resource preservation. Utah agencies involved in water management began initiating statewide water planning efforts to inventory water resources and to outline water use trends and projections. State agencies also began developing rules and regulations that would support the prevention and control of water pollution, and they became responsible for administering the provisions of the Clean Water Act. Lastly, state and federal agencies also began participating in coordinated efforts to regulate and conserve wetlands and aquatic resources.

In recent decades, Utah agencies have started to support the notion of more integrated planning and management by implementing approaches that encompass large geographic regions, long-term perspectives, a spectrum of socioeconomic and environmental factors, interagency coordination, and stakeholder involvement. Integrated planning and management approaches have proved to be successful in addressing the diverse range of water resources issues that span multiple jurisdictions. The Utah Division of Water Resources (UDWaR) has developed a comprehensive state water plan and 11 detailed river basin plans to assist in the formulation of management strategies and policies. The Utah Department of Water Quality (UDWQ) established Utah’s Watershed Approach for managing and reducing nonpoint source pollution and for improving the condition of watersheds. The UDWQ, in cooperation with the Utah Geological Survey (UGS), developed Utah's Wetland Program Plan (WPP) to support an integrated statewide wetland monitoring and assessment program to improve wetland management and conservation. These efforts have contributed to improvements in water resources and supported more comprehensive frameworks. However, integrated water resources planning and management in Utah remains a challenge due to the suite of laws, policies, and compacts that are administered by numerous federal and state agencies. To continue and advance the development of integrated approaches in Utah, existing policies may need to be reassessed and innovative implementation techniques will need to be devised.

Early Water Management

Management of water resources in the state of Utah predates statehood. In 1847, Mormon (Latter-day Saint) pioneers entered the Great Salt Lake Valley after a westward migration that was prompted by religious persecution (Campbell, 1989a, Hill, 1989). Within days of their arrival to the Salt Lake Valley, Mormon pioneers established base settlements for growing crops and building homes (Alexander, 1996). The first group of settlers quickly realized that water was a scarce commodity and that irrigation systems were the key to establishing self-sufficient agricultural communities in the arid Intermountain West. Extensive irrigation networks composed of ditches, canals, and diversion dams were constructed to reroute perennial stream flows to farmlands (Stene, 1995). The stream in City Creek Canyon, located northeast of downtown Salt Lake City, became the first irrigation and domestic water supply for settlers (Hooton, 1975). By 1860, more than twenty farming communities had been established near the streams of the Wasatch Range and the Jordan River (Thiros, 2010; Moehring, 2004). By 1865, Mormon pioneers had transformed the semi-arid desert landscape by constructing 1,600 kilometers (1,000 miles) of canals to irrigate 6,000 square kilometers (1.5 million acres) of farmland (Hooton, 1999) (Figures 3-1 and 3-2).

During this initial period of water development in Utah, the principal organizer and administrator of water resources was the Mormon Church (Patty *et al.*, 2016). Mormon settlements centered around theological principles and the control of water was vested in church leaders (Hardesty, 1991). Controversies and conflicts over water allocation and water rights were decided in ecclesiastical courts. However, with the establishment of the Territory of Utah in 1850, the roles and responsibilities of water allocations, projects, and rights were delegated to county governments by the Utah Territorial Legislature (Donaldson, 2007). By the late 1860s, the Legislature authorized individual irrigators to organize themselves into irrigation districts and companies that served as cooperative management systems for communities (Fuller, 1994a; Patty *et al.*, 2016).

In 1869, the first Utah land office was opened, which encouraged settlement through the Preemption Act of 1830 and the Homestead Act of 1862. Also, the first transcontinental railroad was completed, which initiated a new wave of settlement (Anderson, 1989). As the population grew in the Territory of Utah, competition and conflicts over water increased in frequency, size, and intensity. Therefore, in 1880, the Utah Territorial Legislature abandoned the distinctive communal appropriation system practiced by Mormon settlers and adopted the prior appropriation doctrine of water rights. The prior appropriation doctrine states that water rights are determined by priority of beneficial use, signifying that the first person to use water or divert water for a beneficial use (i.e. agriculture, industry, or domestic) acquires the right to its future use (Donaldson, 2007). This diversion requirement was based on the assumption that legitimate beneficial uses were off-stream, suggesting that instream flows were not recognized as beneficial use by the law (Kenney, 2003).

Shortly after statehood was attained in 1896, water rights were transitioned from an almost exclusively private system to a modern system managed by state law. In 1897, the Utah Legislature established the Office of the State Engineer to improve and clarify the role of the state in the administration, allocation, and development of water resources in Utah (UDWRi, 2009). At the turn of the century, the Utah State Legislature passed a law that required all new appropriations to be approved by the State Engineer (Patty *et al.*, 2016). With this change in legislation, new irrigation systems were built and older systems were repaired and upgraded to meet growing demands. Many farmers and irrigation companies began to embrace the federal support that was provided with the passing of the National Reclamation Act (Newlands Reclamation Act) of 1902 (Fuller, 1994a).

Water Development and Reclamation

A new era of water development in Utah was initiated with the enactment of the National Reclamation Act of 1902. The National Reclamation Act, signed into law by President Theodore Roosevelt, established the United States Reclamation Service (USRS) and authorized the Secretary of the Interior to study and designate irrigation sites in arid regions of the western United States for the purpose of reclaiming lands for productive agricultural use. The Act, which was partially inspired by the agrarian ideals of Thomas Jefferson, founded a reclamation fund from the sale of public lands for the purpose of financing irrigation projects (USBR, 2011). The Strawberry Valley Project, commenced in 1903, marked the beginning of federal aid in Utah and represented the first large-scale trans-mountain diversion from the Colorado River Basin to the Great Basin (Figures 3-3 and 3-4). The Strawberry Valley Project, located in Utah and Wasatch counties, was initiated to provide irrigation water to Utah Valley residents through the construction of Strawberry Reservoir and a series of tunnels, dikes, and canals (Stene, 1995). It was also one of the earliest USRS projects to develop hydroelectric power (USBR, 2016a).

In 1909, the Utah State Conservation Commission, consisting of the Utah Governor and three members, was established by the Utah Legislature. The overall objectives of the Utah State Conservation Commission were to inventory natural resources, to collect and publish statistics relative to the natural resources of the states, to adopt and carry out policies that would prevent the waste of natural resources, and to assist the USRS in establishing dams, reservoirs, and irrigation systems for the reclamation of arid lands in Utah (UCC, 1909; UWPB, 1966). The Utah State Conservation Commission was an attempt by the state to maximize water development and garner federal financial support, while striving to retain state control and initiative (Harvey, 1989). This objective was clearly delineated in the *1909 Preliminary Report of the Utah Conservation Commission*, in which it was stated that "It is hoped that the time will come when practically every drop of water running off Utah mountains may be held back in great reservoirs to be used on the arid lands as irrigation water throughout the summer season."

During the first decade of the twentieth century, population growth and agricultural irrigation in the western United States began to be restricted by water supply constraints (Pegram *et al.*, 2013). The development of the Strawberry Valley Project and numerous other irrigations projects in the Colorado River Basin began to generate significant competition for water claims between the seven states in the Colorado River Basin (Fuller, 1994a). Each of the seven states (i.e. Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming) sought to establish its own limits, and therefore, water disputes continued and differences were not reconciled (Shagren, 1976). Consequently, civic and government officials from the seven states organized the League of the Southwest in 1919 to establish an equitable approach for dividing the waters of the Colorado River (Fuller, 1994b).

In early 1921, the seven states authorized the appointment of commissioners to negotiate a compact for the apportionment of water supplies, thus forming the Colorado River Commission. The State Engineer for Utah, Richard Caldwell, represented Utah. In 1922, the Colorado River Commission negotiated and signed the Colorado River Compact, an agreement that divided the Colorado River Basin into Upper and Lower Basins at Lee Ferry, Arizona. The purpose of the compact was to provide for the equitable division and apportionment of the waters of the Colorado River; to promote interstate cooperation; to remove the causes of controversies; to secure the storage of water and the development of agriculture and industry; and to protect property and life from floods (AZDWR, 2015; Fuller, 1994b).

While Colorado River apportionment negotiations were being deliberated, the Utah Water Storage Commission (UWSC) was established in 1921 to resume some of the responsibilities of the Utah State Conservation Commission, which had been abolished in 1917 (Harvey, 1989). The UWSC was composed of the State Engineer and several governor-appointed citizens from irrigated sections of the state (USDI, 1932). The primary objective of the UWSC was to formulate a plan or program for "the full and proper development and utilization of the state's water supply." The UWSC had many responsibilities, including overseeing water reclamation projects, acquiring necessary water rights, and developing topographic maps of reservoir sites throughout the state (UWPB, 1966; Harvey, 1989; UDWaR, 2001). The UWSC also worked with private and federal interests to prioritize potential projects, to investigate and initiate activity on reclamation projects, and to serve as a negotiator between water users and the USRS (Harvey, 1989).

With the passage of the Colorado River Compact and the completion of the Strawberry Valley Project in 1922, the UWSC and the USRS provided for the federal investigation of a second reclamation project in Utah. In 1923, the USRS was renamed the United States Bureau of Reclamation (USBR), and in 1924, the UWSC and the USBR authorized the Weber River Project, an undertaking which included the construction of Echo Dam and the Weber-Provo Diversion Canal (USBR, 2011; Eastman, 2009a; McCune, 2000). The Weber River Project was completed in 1931, but financial hardships that resulted from the Great Depression deferred further reclamation projects in Utah until the National Industrial Recovery Act (NIRA) was passed in 1933. Under NIRA, President Franklin Roosevelt and the USBR authorized the construction of the Hyrum Project (1933-1935), Ogden River Project (1933-1936), Provo River Project (1935-1958), Moon Lake Project (1933-1938), and Sanpete Project (1935-1939) (Cannon and Embry, 2008).

Some of these reclamation projects only became attainable after the UWSC persuaded the federal government to direct resources from the Federal Emergency Administration and Public Works Fund. The UWSC, which operated from 1921 to 1941, approved and coordinated all Utah projects undertaken by the USBR (Harvey, 1989). In 1941, the Utah Legislature abolished the UWSC and temporarily assigned the responsibility of overseeing water reclamation project to the Publicity and Industrial Development Department (UDWaR, 2007; UWPB, 1966). In 1947, the Utah Water and Power Board (UWPB) was created to continue the mission of the UWSC (UDWaR, 2001). The UWPB was tasked with the responsibility of promoting the development, utilization, conservation, and protection of water resources in Utah (UDARS, 2016). The UWPB was also provided with a revolving construction fund which was to be allocated to small water storage and conservation projects. The roles of the agency were eventually expanded to include the negotiations and administration of interstate compacts (UWPB, 1966).

Beginning in 1946, commissioners from the states of Utah, Colorado, Wyoming, New Mexico, and Arizona formed the Upper Colorado River Commission and convened for the purpose of establishing an agreement regarding the allocation of water in the Upper Colorado River Basin (Shagren, 1976). In 1948, the Upper

Colorado River Basin Compact was signed, with Edward Watson, State Engineer of Utah, and Grover Giles, Attorney General, representing the state of Utah (Bingham, 1960). The Upper Colorado River Basin Compact divided the water apportionments to the Upper Basin states by percentage of available water rather than establishing acre-foot apportionments. As part of the passage of the Upper Colorado River Basin Compact, the Upper Colorado River Commission was established as a permanent interstate administrative agency with the purpose of resolving disagreements, curtailing water uses to meet compact compliance, and representing interests (Hobbs, 2009).

In 1956, the Colorado River Storage Project Act was enacted, which authorized the USBR to construct, operate, and maintain the Colorado River Storage Project (CRSP). The CRSP, one of the most complex and extensive multi-purpose river development projects in the world, allowed for the comprehensive development of water resources in the states of the Upper Colorado River Basin. The CRSP authorized the construction of massive hydrological infrastructure, including Glen Canyon Dam on the Colorado River (Figure 3-5), Flaming Gorge Dam on the Green River (Figure 3-6), Navajo Dam on the San Juan River, and Blue Mesa, Crystal, and Morrow Point dams on the Gunnison River. The CRSP was established to provide long-term regulatory water storage for the purpose of regulating the Colorado River, storing water for beneficial use, providing for the reclamation of arid lands, controlling floods, and generating hydroelectric power (USBR, 2016b).

Under the CRSP, portions of the Central Utah Project (CUP) were authorized for construction. The CUP was and is still considered the largest, and most controversial, federal reclamation project in the state of Utah. The project plan called for diversions of a portion of Utah's share of water from the Colorado River. A collection system composed of aqueducts, tunnels, and dams was planned to divert water from the southern slopes of the Uinta Mountains and the Colorado River to the Wasatch Front for irrigation, domestic, and industrial use (Shagren, 1976). Construction of the CUP began in 1959, but progress was gradual because extensive planning and investigations were required; water rights needed to be acquired; and legislative and financial hurdles were common (Eastman, 2006). In 1964, the Central Utah Water Conservancy District (CUWCD) was organized to manage water distribution, administer the repayment of federal funds, and operate and maintain facilities. Due to the size and complexity of the CUP, the CUWCD and the USBR divided the CUP into six units to facilitate planning and construction (Kichas, 2015). The six units included Vernal, Jensen, Bonneville, Upalco, Ute Indian, and Uintah. The Vernal, Jensen, Bonneville, and Upalco units were authorized under the 1956 Colorado River Storage Project Act, while the Ute Indian and Uintah were later authorized by the 1968 Colorado River Basin Project Act (CUPCAO, 2016a).

Beginning in the 1960s, environmental considerations about the CUP began to surface (Murray and Johnston, 2001). Much of the early concern came from the Utah Division of Wildlife Resources (UDWR) and the United States Forest Service (Eastman, 2006). Although other national demands, such as the Vietnam War, restricted funds for water development and reclamation projects, Congress continued to authorize the Weber River Project and several CUP projects (Fuller, 1994b). However, with the enactment of the National Environmental Policy Act

(NEPA) in 1969, the USBR was required to complete environmental investigations (i.e. environmental assessments and environmental impact statements). While the USBR completed investigations for CUP projects and proposed mitigation measures, environmental interest groups challenged the findings and filed a lawsuit in 1973 (Eastman, 2006).

While the courts ruled in favor of the USBR in 1974, President Gerald Ford (1974-1977) deferred the budget for the CUP (Fuller, 1994b). During the following administration, President Jimmy Carter nearly withdrew all financial support for the CUP during his years in office (1977-1981). Within months of being elected, President Carter issued a list of water development projects, including the CUP, that were proposed for defunding due to environmental, social, and fiscal impacts. He affirmed that the CUP posed serious environmental damage and complicated the Ute Indian claims to water. The list produced significant controversy and instigated debates on the benefits of federal water development projects. President Carter later revised his recommendations and developed a compromise in which the CUP would need to be reevaluated and amended (Eastman, 2006).

During the 1980s, the Jensen Unit with its primary facility, Red Fleet Reservoir, was completed. Facilities in the Vernal Unit, which were completed in 1966, continued to be maintained and improved with the development of recreational facilities and the stabilization of Steinaker Dam (Eastman, 2006). The Upalco, Ute Indian, and Uintah units had been postponed indefinitely due to changing political climates, budget priorities, and emerging environmental concerns (Eastman, 2009a). Construction of the Bonneville Unit, which was initiated in 1968, continued as the vast network of reservoirs, aqueducts, tunnels, canals, pipelines, pumping plants, and conveyance facilities expanded (URMCC, 2016a). By 1985, the Bonneville Unit had become the largest and most complex of the authorized units (Figure 3-7), and the cost had exceeded allotted funds, placing financial strains on the federal government to meet project funding needs (Patty *et al.*, 2016). Consequently, state and local officials requested Congress to make an unprecedented change (Murray and Johnston, 2001).

In 1992, Congress responded to state and local request by enacting the Central Utah Project Completion Act (CUPCA). Due to the size, complexity, expense, and highly controversial nature of the CUP, planning and construction phases of the various units spanned decades. Projects continued to be delayed as a result of environmental legislation, lawsuits, and decreasing federal support (Eastman, 2006). With the passage of the CUPCA, the CUP was allowed to proceed as long as significant concerns were addressed. Under the CUPCA, Congress, for the first time in history, designated a local conservancy district as the planning and construction entity for a major federal water project. The responsibility was removed from the USBR and transferred to the CUWCD, with direct oversight by the Department of the Interior (CUPCAO, 2016b). The CUPCA established the Central Utah Project Completion Act Office to oversee completion of the project and to administer funding. Also, the CUPCA deauthorized several irrigation projects, including the Ute Indian Unit, and required 35 percent local cost sharing, water conservation requirements, and environmental mitigations (USDI, 2012; SLC, 2016).

The enactment of the CUPCA signified a shift in water resources management in Utah in which traditional reclamation projects became obsolete and environmental mitigation became an integral component of planning (Eastman, 2006). As part of the CUPCA, the Utah Reclamation Mitigation and Conservation Commission (URMCC) was established in 1994 as an executive branch agency of the federal government. The URMCC was established in response to the awareness that prior CUP mitigation efforts were inadequate when measured against modern environmental standards. The primary purposes of the URMCC, as a central mitigation agency, are to support environmental programs and comprehensive resources planning and to design, fund, and implement mitigation projects that are required to offset the impacts to fish, wildlife, and recreation resources caused by the CUP and other federal reclamation projects in Utah (URMCC, 2016b).

State Water Planning

State water planning in Utah was not formally established until the 1960s. In 1962, a joint study between the UWPB and the Engineering Experiment Station at Utah State University was initiated to complete an exploratory review and evaluation of Utah's water resource problems, possibilities, and challenges. A preliminary comprehensive inventory, which was based on the best scientific data at the time, was compiled and published in the 1963 report entitled *Developing a State Water Plan: Utah's Water Resources – Problems and Needs – A Challenge* (UWRL, 1963). Concurrently, during the Utah Legislative Session of 1963, legislation was passed that set aside funds for the UWPB to formulate a state water plan in cooperation with other state agencies using water resource data from state and federal agencies and research institutions (Utah Code §73-10-15). The report provided a crucial foundation for future water resources planning in the state of Utah, and the legislation prompted a statewide reconnaissance of water resources (UDWaR, 2001).

With the creation of the Utah Department of Natural Resources (UDNR) in 1967, the Utah Legislature renamed the UWPB as the Board of Water Resources and established the UDWaR (Strong, 2009). The UDWaR was charged with the responsibility of conserving and developing water resources, comprehensive water planning, and coordinating interstate negotiations (Carr *et al.*, 1987). The Board of Water Resources, consisting of governor-appointed representatives from designated geographic areas of the state, was appointed as the policymaking body of the UDWaR (Strong, 2009).

Between 1972 and 1985, the UDWaR continued water planning efforts in Utah by publishing a series of reports entitled *The State of Utah Water*. A total of six consecutive reports were published during this period which outlined and refined water supply and use estimates and identified potential water use, development, and redistribution projects in the state of Utah. In the 1985 report, *State of Utah Water 1985*, the UDWaR defined water resource planning as "the process of establishing long-range objectives to assure the highest use of water for the public benefit." It was also noted that the increasing demands for water made it imperative to accelerate the development and implementation of a state water plan (UDNR, 1985). In 1984 and 1985, the Utah Legislature established an interagency planning committee, the State Water Plan Coordinating Committee (SWPCC), to develop a coherent state water plan. In 1987, the SWPCC, composed of members from several state agencies, began developing the state water plan (SWPCC, 1990). After extensive revisions, the plan was solidified and approved in 1990 and a landmark document entitled *Utah State Water Plan* was published. This document identified a set of guiding principles for water resources planning, provided water resource inventories, outlined water use trends, identified water conservation measures and development projects, addressed the physical, economical, sociological, and environmental dimensions of water use, and provided the foundation for more detailed planning in 11 hydrologic river basins in Utah (UDWaR, 2001; UDNRE, 1982, UWRL, 1990).

In 2001, the state water plan was updated by the UDWaR, and a report entitled *Utah's Water Resources: Planning for the Future* was published. Between 1990, when the first state water plan was published, and 2001, when the state water plan was updated, 11 detailed river basin plans were prepared. The 11 river basin plans are based on hydrologic units, as defined by the United States Geological Survey (USGS). However, some modifications were made by UDWaR to account for inter-basin exchanges and trans-basin diversions (Figure 3-8). The river basin plans included Bear River Basin (1992), Cedar/Beaver Basin (1995), Jordan River Basin (1997), Kanab Creek/Virgin River Basin (1993), Sevier River Basin (1999), Southeast Colorado River Basin (2000), Uintah Basin (1999), Utah Lake Basin (1997), Weber River Basin (1997), West Colorado River Basin (2000), and West Desert Basin (2001).

These detailed river basin plans, which involved significant data collection, extensive interagency cooperation, and public outreach efforts, outlined information on water supplies, water use, and issues identified by local stakeholders. Since 2001, five of the basin plans have been updated to reflect more precise assessments and the changing supplies and demands. These comprehensive plans have been and continue to be used by local and statewide planners and legislators to formulate management strategies and policies, to reach informed decisions, to improve water conservation, and to plan for the future of water resources in Utah (UDWaR, 2001; USACE, 2009).

Water Quality Management

The first legislative program for controlling water pollution in Utah was enacted in 1953 with the passage of the Utah Water Pollution Control Act (UWPCA). The UWPCA expressly recognized that water pollution was a public nuisance and it was contrary to the state policy of protecting, maintaining, and improving the quality of waters. The UWPCA provided for the establishment of the Utah Water Pollution Control Committee (UWPCC) and the Utah Bureau of Water Pollution Control (UBWPC). The UWPCC was established as a policymaking body to develop rules and regulations that would support the prevention, control, and abatement of water pollution. The UWPCC developed an extensive system for the classification of state waters according to their designated uses and established water quality standards for each classified use. The UBWPC, under the supervision of the UWPCC, became responsible for regulating the discharge of pollutants into Utah waters (SWPCC, 1990; Radosevich and Skogerboe, 1978; Utah Code §73-14-6).

In 1972, the Federal Water Pollution Control Act of 1948, the first successful law to address water pollution in the United States, was significantly reorganized and expanded. With further amendments in 1977, the legislation became known as the Clean Water Act. The revised Act provided a structure for regulating pollutant discharges and authorized the United States Environmental Protection Agency (USEPA) to implement pollution control programs (USEPA, 2016a; Paulson *et al.*, 1993). Under the Clean Water Act, the UWPCC and UBWPC became responsible for defining water quality criteria; developing water pollution control programs; monitoring and documenting the quality of waters; developing an anti-degradation policy; developing a list of impaired waters; and submitting biennial reports to the USEPA. Of particular note, Section 303(d) of the Clean Water Act began requiring states to identify waters that were not attaining beneficial uses according to state water quality standards, and Section 305(b) began requiring states to summarize the condition of surface waters (UDEQ, 2016a; UDWQ, 2016).

While the Clean Water Act provided direction to state agencies for controlling water pollution, the primary orientation of the Act was toward point source pollution. The USEPA had not been authorized to regulate nonpoint source pollution, which was still regarded by Congress as a state responsibility (Poe, 1995). Consequently, in 1987, Congress amended the Clean Water Act to establish the Section 319 Nonpoint Source (NPS) Management Program to provide greater federal leadership for assisting states and local governments in addressing nonpoint source issues. Under the Section 319 NPS Management Program, a federal grant program was created that provided funds to states for developing and implementing

NPS management programs (USEPA, 2016a). Accordingly, in 1990, the state of Utah developed an NPS Management Program that was focused on improving the quality of impaired waterbodies. The Utah NPS Management Program was created with the overall goal of protecting, restoring, and enhancing the waters in Utah through the prevention and reduction of sources of polluted runoff (UDEQ, 2013; UDEQ, 2016a).

In 1991, the Utah Legislature passed the Utah Water Quality Act and established the Utah Department of Environmental Quality (UDEQ) to protect public health and quality of life by maintaining and enhancing the environment. As part of the UDEQ, the UDWQ was created, replacing the UBWPC, and the Utah Water Quality Board was established to replace the UWPCC (UDWaR, 2001). The Utah Water Quality Board, composed of representatives from water quality stakeholder groups, was formed to guide the development of water quality policy and regulations. The UDWQ, under the supervision of the Utah Water Quality Board, was designated as the lead agency in managing the water pollution control program set up by state statue and in carrying out the provisions of the Clean Water Act (UDEQ, 2016a; UDEQ, 2013). Specific responsibilities under the Clean Water Act include the development and implementation of water quality management plans; the certification and enforcement of effluent discharge permits; and the administration of various water quality monitoring programs (SWPCC, 1990).

In 1994, the UDEQ and UDWQ established Utah's Watershed Approach for managing and reducing nonpoint source pollution in Utah. Utah's Watershed Approach is modeled after the USEPA Watershed Approach (as discussed in Chapter 2). The USEPA Watershed Approach was established in 1991 as a comprehensive water resources management strategy that would provide state and tribal agencies with a flexible framework for restoring watersheds, promoting coordination, and balancing objectives (USEPA, 1991). Utah's Watershed Approach, which has been fundamental in guiding the Utah NPS Management Program, has become an integrated statewide watershed management approach that is directed toward improving the protection of surface and ground water resources in Utah (UDEQ, 2001). Utah's Watershed Approach was established with the intent of providing better coordination and integration of agencies, stakeholders, and water quality programs; supporting more innovative, responsive, and cost-effective solutions to water quality problems; establishing a framework that would provide state agencies with the capability to meet the NPS guidelines as established by the USEPA; and fostering environmental stewardship (UDEQ, 2013).

Within Utah's Watershed Approach, a series of 12 nested management units have been defined by UDEQ and UDWQ to provide a spatial focus for managing pollution in the context of watershed basins (Figure 3-9). These management units are fairly consistent with the 11 hydrologic basins that were defined by the UDWaR for state water planning; however, there are some slight inconsistencies. A few of the names are different and there are some boundary differences along the Wasatch Front and in the southeast region of the state. The 12 management units include Bear River, Cedar/Beaver, Colorado River Southeast, Colorado River West, Great Salt Lake Desert/Columbia, Great Salt Lake, Jordan River, Lower Colorado River, Sevier River, Uinta Basin, Utah Lake, and Weber River (UDEQ, 2016b). These management units provide the UDWQ with an improved perspective for determining environmental objectives and evaluating the impacts of ecological stressors (MSE, 2007).

The key features of Utah's Watershed Approach are stakeholder involvement, intensive monitoring, problem targeting and prioritization, and watershed management planning and implementation (Figure 3-10). Stakeholder involvement plays a pivotal role in the identification of issues and in the success of the implementation plan and the restoration of water quality (MSE, 2007). Intensive monitoring, which presently occurs on a six-year rotating basin schedule, ensures that robust datasets are developed and contributes to more accurate assessments of watershed condition (UDEQ, 2016a). Watershed assessments, which are generally derived from monitoring data and predictive water quality modeling, provide an estimation of water quality conditions. Data are compared against state water quality standards to determine status, and if impairment is identified, sources and causes of pollutants are identified. Impaired waters and problem areas are targeted and prioritized based on level of importance. Watershed plans, which identify integrated management solutions for priority areas to reduce pollutant levels, are developed to provide direction for improving water quality. Plan implementation provides detailed actions, such as stream restoration, and a schedule for carrying out the plan (UDEQ, 2013).

The NPS Management Program and Utah's Watershed Approach are presently administered by the UDWQ through collaboration and assistance from the Utah Water Quality Task Force. The Utah Water Quality Task Force, which consists of representatives from state, federal, and private agencies and organizations, facilitates the protection and restoration of surface and ground water through coordinated and holistic watershed management (UWQTF, 2015). The collective objectives of the UDWQ, the Utah NPS Management Program, and Utah's Watershed Approach are to conserve the waters of the state; to protect, maintain, and improve the quality of waters in the state; and to provide for the prevention and control of pollution. These goals are attained through the coordination of local, state, and federal agencies and private entities; through the support of state and local watershed coordinators and groups, such as the Utah Watershed Coordinators Council; and through the implementation of voluntary- and incentive-based approaches that employ preventive techniques and mitigation measures (UDEQ, 2013). Watershed-based perspectives and frameworks adopted and employed by the UDEQ and UDWQ continue to improve and guide integrated water quality management in the state of Utah (UDEQ, 2016a).

Wetland Regulation, Conservation, and Planning

Although wetlands constitute a minor component of the landscape in Utah, they provide a wide range of ecological, economic, social, and cultural benefits and services (UGS, 2016; Clarkson *et al.*, 2013). Wetlands improve the quality of water; they maintain water regimes and the hydrology of watersheds; they maintain water table levels and baseline flows by recharging and discharging groundwater supplies (Sheldon *et al.*, 2005; Wright *et al.*, 2005); they can buffer the impacts of urban development by collecting and counteracting the increased runoff from impervious surfaces (USEPA, 2013); and they provide important breeding, spawning, foraging, and nesting habitat for aquatic, terrestrial, and avian species (Sheldon *et al.*, 2005; Wright *et al.*, 2005).

Despite the numerous benefits provided by wetlands, they were frequently considered an impediment to agricultural, industrial, and urban development. Up until the latter half of the twentieth century, ambitious engineering, innovative technology, and political and financial incentives promoted the widespread drainage and destruction of wetlands. The federal government subsidized or facilitated wetland losses through public works projects, technical practices, and drainage programs (Dahl and Allord, 1997). Wetland inventories have suggested that roughly half of all wetlands in the conterminous United States have been drained or filled since colonization. In Utah, it has been estimated that approximately 30 percent of wetlands have been drained, excavated, or filled (Dahl, 1990). Some estimates indicate that as much as 58 percent of historic wetlands in the Great Salt Lake Ecosystem have been lost (TOI, 2006). The rates of wetland loss in the United States were immense up until the 1970s, but they began to slow during the 1980s as conservation efforts were initiated, environmental awareness increased, and the direction of the federal government changed (Dahl and Allord, 1997; Dahl, 2011).

The federal government began to protect wetlands directly and indirectly through regulation, by acquisition, and through incentives and disincentives (Votteler and Muir, 1996). The Clean Water Act, specifically Section 404, became the primary means for wetland regulation. Through Section 404, the USEPA and United States Army Corps of Engineers (USACE) began to jointly regulate wetland activities by controlling the discharge of dredged or fill materials into wetlands and other waters (USEPA, 2016b). Additionally, a number of programs and statutes have provided for wetland acquisition, restoration, and conservation. Executive orders, including 11988 (Floodplain Management) and 11990 (Protection of Wetlands), have required agencies to minimize impacts of federal activities on wetlands. Legislation, such as the Food Security Act of 1985, eliminated incentives and ended federal assistance for wetland conversion (Votteler and Muir, 1999).

Although several federal programs and policies have been developed for regulating and protecting wetlands, they have typically not been effective in preventing the continued losses due their limited scopes (APA, 2002; Votteler and Muir, 2002). The federal statutes that presently regulate or protect wetlands were often intended for other purposes and a cohesive national wetland protection policy has not been developed (Mitsch and Gosselink, 1993). Therefore, some states have established legislation, regulations, or programs to support improved wetland management and protection. State and local governments have the ability to establish programs that are more restrictive and inclusive than federal regulations and policies. However, state wetland legislation and programs vary in capacity and magnitude. While some state programs are comprehensive, others are limited and may solely rely on the provisions of the Clean Water Act (ELI, 2008).

In the state of Utah, specific wetland legislation and policies have not been enacted or adopted to guide wetland regulation; therefore, wetland regulation generally mirrors federals law. The UDWQ and the Utah State Water Quality Board are the primary entities responsible for wetland management and regulation. Wetlands have been managed as waters of the state under Utah's water quality standards, and more recently, they have generally been protected by narrative standards that maintain aquatic wildlife through designated uses (UDEQ, 2014). The USACE and USEPA jointly administer and enforce the federal dredge and fill permits under Section 404 of the Clean Water Act in Utah. However, the UDWQ and the Utah State Water Quality Board have the authority to approve, deny, or waive water quality certifications under Section 401 of the Clean Water Act. The purpose of the Section 401 certification is to ensure that federally permitted or licensed activities comply with Utah's discharge and water quality requirements (UDEQ, 2009; ELI, 2008; UDEQ, 2016c).

Since state-specific wetland legislation is limited in Utah, federal and state agencies, non-governmental organizations, and environmental groups have been proactive in supporting non-regulatory approaches to wetland conservation, including land acquisition, stewardship, land-use planning, and education (Lee, 2001). The first and foremost instance of wetland acquisition in the state of Utah was with the establishment of the Bear River Migratory Bird Refuge. The benefits of the Great Salt Lake Wetlands in northern Utah were recognized early on by state and federal agencies and sportsmen organizations. Due to the significant losses of marshes during the first two decades of the twentieth century, the Bear River Migratory Bird Refuge was established in 1928 by Presidential Proclamation to be maintained as a refuge and breeding grounds for migratory birds (Wilson and Carson, 1950). The Bear River Migratory Bird Refuge is managed by the United States Fish and Wildlife Service (USFWS) and encompasses nearly 32,500 hectares (80,000 acres) of critical wetland and migratory bird habitat (USFWS, 2016).

Beginning in the late 1920s, Utah agencies began establishing a series of Waterfowl Management Areas (WMAs) to preserve and restore wetlands, to provide habitat for nesting and migratory birds, to provide designated waterfowl hunting grounds, and to construct wetlands in order mitigate for previous losses. Public Shooting Grounds (established in 1929), Locomotive Springs (established in 1931), Farmington Bay (established in 1935), and Ogden Bay (established in 1937) were the first four WMAs to be founded in Utah. There are presently 13 WMAs, with eight of them located within of the Great Salt Lake Ecosystem. The majority of these WMAs are intensively managed by the UDWR; however, some areas are managed under cooperative agreements with other state and federal agencies, such as the Utah Division of Forestry, Fire and State Lands (UDFFSL) and the Bureau of Land Management (BLM). Management activities within WMAs largely include the conservation and restoration of wildlife and aquatic habitat, monitoring and improvement of water resources, and environmental education and outreach (DuFault *et al.*, 2000; Lock *et al.*, 1993; ELI, 2008).

Wetland conservation and restoration efforts in Utah began to increase in the 1990s. The Nature Conservancy, National Audubon Society, URMCC, and Rio Tinto Kennecott have supported the acquisition, restoration, and creation of valuable wetland habitat. The Nature Conservancy and the URMCC partnered in 1994 to expand the Great Salt Lake Shorelands Preserve, an area of critical wetland and upland habitat along the eastern shore of the Great Salt Lake (TNC, 2016; URMCC, 2016c). In 1995, the National Audubon Society created the Gillmore Sanctuary from a land donation. The National Audubon Society partnered with URMCC to expand the Sanctuary to create the South Shore Ecological Reserve, an area on the south and east shores of the Great Salt Lake. Additional land was purchased by URMCC, Rio Tinto Kennecott, and the Salt Lake Airport Authority through the need mitigate for impacts to and losses of other wetlands (Williams, 2015; DuFault *et al.*, 2000; URMCC, 2016c). In 1996, the URMCC partnered with The Nature Conservancy, UDWR, USBR, BLM, and USFWS to establish the Utah Lake Wetland Preserve, a network of wetland and upland habitats near the southern end of Utah Lake. The Preserve was created to partially mitigate for impacts from the CUP (URMCC, 2016c; Lee, 2001). In 1998, the Kennecott Inland Sea Shorebird Reserve was created under a mitigation plan developed by Rio Tinto Kennecott and the USACE to offset wetlands losses (RTK, 2008; DuFault *et al.*, 2000). In addition to these large land acquisitions, several private entities have supported wetland conservation (DuFault *et al.*, 2000).

While conservation efforts have been somewhat successful in preserving and restoring significant wetlands in Utah, wetland planning efforts have been required to support comprehensive management and to improve scientific understanding (Lee, 2001). In 1997, the Great Salt Lake Planning Project (GSLPP) was initiated to develop a Comprehensive Management Plan for the Great Salt Lake Ecosystem. The primary purposes of the GSLPP were to establish unifying management objectives, to coordinate planning and management between Utah agencies, and to develop a management plan that supported sustainability and multiple use. An integral component of the GSLPP was to determine a wetland policy framework that would address the inadequacies provided by federal regulation and provide added measures of protection (Clarke *et al.*, 2000). In 2000, *The Great Salt Lake Comprehensive Management Plan* was published by the UDNR and UDFFSL with an overarching goal of protecting and sustaining natural resources within the Great Salt Lake Ecosystem (DuFault *et al.*, 2000).

In 2004, the UDWQ initiated Utah's Wetlands Program to evaluate the ecological and biological characteristics of wetlands associated with the Great Salt Lake and to improve wetland understanding and management. Between 2004 and 2009, extensive research was undertaken as part of the Great Salt Lake Wetlands Research Program to assess several wetland parameters, such as water quality, shorebird and waterfowl habitat, and macroinvertebrate communities. These studies resulted in the development of a preliminary assessment framework that was designed to integrate physical, chemical, and biological characteristics of wetlands. In 2012, the UDEQ launched the Great Salt Lake Water Quality Strategy to improve upon the assessment; to fill critical knowledge gaps; to improve water quality management decisions; to reduce regulatory uncertainties; and to improve coordination and stewardship. The Strategy provided improved scientific understandings that could be used (1) to develop wetland-specific water quality standards, (2) to design innovative approaches for evaluating the effectiveness of management practices, and (3) to support and refine Utah's Wetland Program Plan (WPP) (UDEQ, 2014).

Utah's WPP has been instrumental in changing management perspectives and supporting more integrated action. WPPs are voluntary plans developed by state agencies under the direction of the Wetlands Division of the USEPA to support wetland program goals. Utah's WPP was jointly developed by the UDWQ and the Utah Geological Survey (UGS) in 2010 and submitted to the USEPA for approval as a five-year plan (2011-2016) for the purpose of supporting integrated wetland conservation, management, and restoration in Utah. The general objectives of Utah's WPP are to direct wetland program development activities; to coordinate a comprehensive strategy for monitoring and managing wetlands that is consistent with the environmental and natural resource goals of Utah; to serve as a tool for communication and collaboration with other agencies and non-governmental organizations involved in wetland research, conservation, and protection; and to gain stakeholder acceptance. Specific efforts of Utah's WPP are focused on developing scientifically validated tools to describe the abundance, health, and function of wetlands. These scientifically-validated tools will be incorporated into wetland monitoring protocols that will then be used to assess the conditions of wetlands within the state of Utah. Assessments of wetland conditions will be used to improve the understanding of baseline wetland conditions, to develop benchmarks for wetland restoration and mitigation, to prioritize wetland restoration and protection efforts, and to inform the development of wetland-specific water quality standards (Hooker and Jones, 2013).

The improved scientific understanding acquired from comprehensive planning, extensive research studies, and actions items associated with Utah's WPP have provided the UDWQ with additional insight as to how wetlands in Utah should be managed. The UDWQ has recognized that previous approaches to wetland management, which have been based on existing water quality standards, have been problematic and that novel approaches are necessary for the protection of wetlands and aquatic wildlife in Utah. Therefore, the UDWQ is in the process of developing and implementing a more integrated watershed-based approach to managing, protecting, and restoring wetlands in Utah, particularly those associated with the Great Salt Lake. This watershed-based approach is congruent with Utah's Watershed Approach to managing and reducing non-point source pollution because it is a multi-faceted strategy that supports comprehensive management, stakeholder involvement, and interagency coordination. Specific objectives of this watershed-based approach to managing wetlands are to foster adaptive management; to refine water quality standards and monitoring methods to properly reflect the unique characteristics of wetlands; and to develop a monitoring assessment framework that will enhance the reporting process and that will support informed decision-making based on broad-based ecosystem goals (Hooker, 2017).

Conclusion

Water resources planning and management in Utah has experienced several transitions since the region was settled by Mormon pioneers. During the initial colonization period, the practice of irrigation transformed the arid landscape to support cooperative self-sufficient agricultural communities. The absence of an established government and a water rights system allowed Mormon settlers to establish institutional arrangements and engineering solutions that were centered around theological ideologies. With the passage of homesteading legislation and the completion of the first transcontinental railroad, settlement was promoted and encouraged in the arid Intermountain West. Population growth generated significant competition for water resources, and eventually, the Utah Legislature and the federal government intervened. Despite the escalating conflicts over water resources, the federal government continued to endorse settlement in the arid regions of the United States.

The enactment of the National Reclamation Act of 1902 indefinitely changed the landscape and hydrology of the Intermountain West and Colorado River Basin. Water development projects were constructed to reclaim arid lands for productive agricultural use. State agencies in Utah favored the notion of reclaiming lands through the construction of dams, reservoirs, and irrigation systems. The idea of maximizing water development and minimizing downstream flows was appealing. However, this aspiration, accompanied with the insatiable consumption of water, triggered a series of interstate negotiations that promoted the equitable division and apportionment of water within the states of the Colorado River Basin. Interstate compacts paved the way for large-scale, multi-purpose hydrological infrastructure projects that were constructed to provide long-term regulatory storage, irrigation water, and hydroelectric power. The CUP, considered the largest and most controversial federal reclamation project in Utah, became the primary focus of water development in Utah. CUP developments, spanning decades and geographic scales, have altered hydrologic systems through trans-mountain and trans-basin water diversions and were frequently constructed with minimal regard to environmental consequences.

An upsurge in environmental awareness and legislation promoted a shift away from strict engineering solutions to water management. This shift instigated changes in federal and state agency perspectives. The federal government allocated fewer funds for water development projects and began adopting different approaches to managing water resources. Utah officials were slower to make changes and continued to be captivated by the concept of maximizing water potential. However, with growing water shortages and disputes, the UWPB and the Engineering Experiment Station at Utah State University began compiling scientific data to support statewide water planning efforts. Concurrently, the UBWPC and the UWPCC began implementing federal and state water policies and regulations that would support the prevention, control, and abatement of water pollution. Federal and state agencies also began instituting coordinated conservation measures to regulate wetland activities and to conserve wetlands and aquatic habitat.

With the creation of the UDNR in 1967 and the UDEQ in 1991, and with several administrative reorganizations occurring between those years, the Utah Legislature and state agencies started espousing more balanced views of water resources. These views have progressed over decades and have evolved into more flexible frameworks that support integrated management. In general, integrated approaches to water resources management are characterized by hydrologically-defined management units, a balance between long-term conservation and development objectives, interagency coordination and collaboration, stakeholder involvement, and holistic management strategies. Utah state water planning goals, although initially focused around inventorying water resources and identifying potential water development projects, have been revised to reflect changing needs and perspectives. Since 1990, the UDWaR has provided for detailed investigations of

11 river basins in Utah. These detailed river basin plans reflect integrated action in that they comprise essential information regarding the future of water resources in Utah and they involved extensive interagency cooperation, public outreach, and stakeholder involvement to identify issues.

In 1994, the UDEQ and UDWQ established Utah's Watershed Approach for managing and reducing nonpoint source pollution. Utah's Watershed Approach, modeled after the USEPA Watershed Approach, was instituted to guide the Utah NPS Management Program and to improve the quality of surface and ground water resources in Utah. Utah's Watershed Approach is the epitome of integrated water resources management in that it encompasses an overarching goal of improving the condition and health of watersheds in Utah through the holistic management of hydrologically-defined management units. This approach also supports extensive stakeholder involvement, inter-agency collaboration and partner coordination, and the development of responsive and long-term solutions to water quality problems.

Beginning in 2004, the UDEQ and UDWQ initiated Utah's Wetlands Program to improve scientific understanding and management of wetlands in Utah. The Wetlands Program supported extensive research and provided for the development of an assessment framework to improve wetland-specific water quality management decisions. These efforts supported the development of Utah's WPP. Utah's WPP was drafted to direct wetland program development activities and to support integrated wetland conservation, management, and restoration. The scientific studies associated with Utah's Wetlands Program and the action items associated with Utah's WPP have provided the foundation for an integrated watershed-based approach to wetland management in Utah. The watershed-based approach is congruent with Utah's Watershed Approach and includes a multi-faceted and tangible framework for managing wetlands based on adaptive management and wetland-specific water quality standards.

Integrated approaches and strategies developed by agencies within the UDNR and the UDEQ have promoted the improvement of water quality and watershed condition. However, despite considerable strides over the decades, integrated management remains problematic in Utah and in other arid regions of the United States. Challenges are present due to the scarcity of water; the significant number of laws, policies, and compacts; the involvement of several federal and state agencies; and the vast array of political, economic, and social factors and opinions that span local, regional, and state levels. For integrated approaches to progress and evolve in Utah, challenges will need to be addressed through the re-evaluation of existing policies, regulations, and approaches, as well as through the development of innovative, dynamic, and streamlined frameworks and implementation strategies. Streamlined frameworks and implementation strategies can enhance the planning and management process, improve intra-agency and interagency coordination, and effectively account for stakeholder perspectives.

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Figures

Figure 3-1. Salt Lake and Jordan Canal, 1909. Source: Salt Lake City Engineers Photograph Collection, Utah State Historical Society.

Figure 3-2. Salt Lake City 1000 South Canal, 1913. Source: M.B. Ellerbeck, Utah State Historical Society.

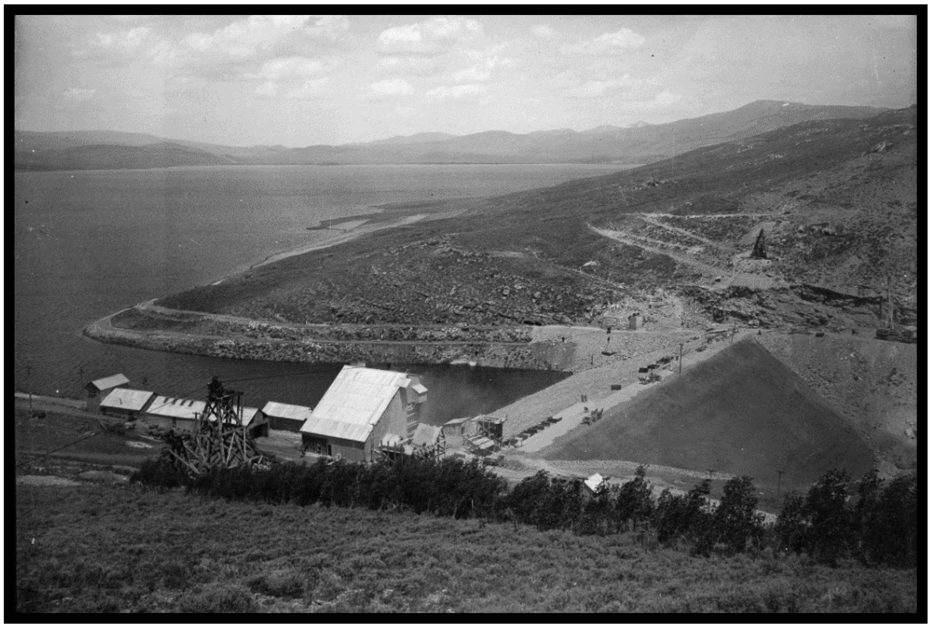

Figure 3-3. Strawberry Dam and Construction Camp, 1912. Source: Library of Congress, Historic American Engineering Archive (Call Number: HAER UTAH, 25-PAYS, 1--8).

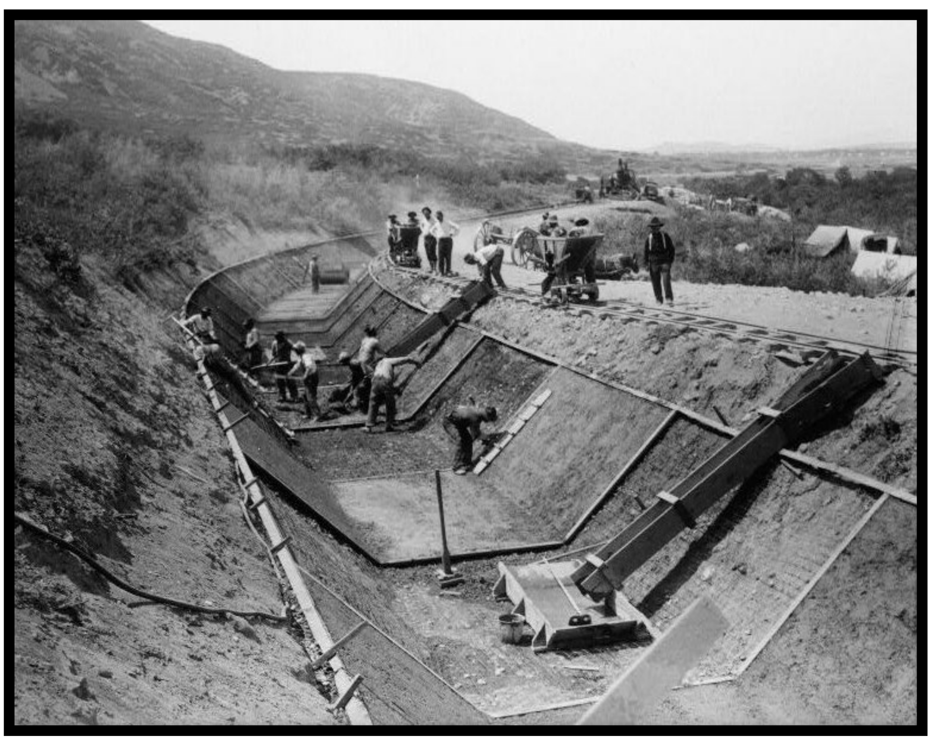

Figure 3-4. Strawberry Valley Project, preparing the High Line Canal for concrete lining, 1915. Source: Library of Congress, Historic American Engineering Archive (Call Number: HAER UTAH, 25-PAYS, 1--31).

Figure 3-5. Glen Canyon Dam, 1965. Source: Bureau of Reclamation Photograph Collection, Utah State Historical Society.

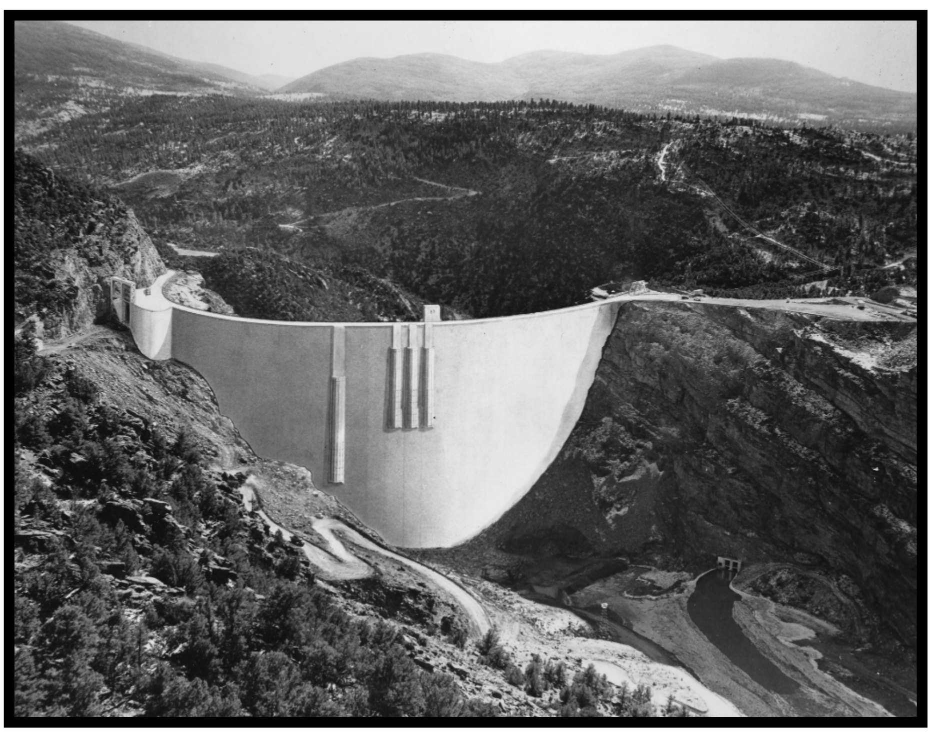

Figure 3-6. Flaming Gorge Dam, 1960. Source: Bureau of Reclamation Photograph Collection, Utah State Historical Society.

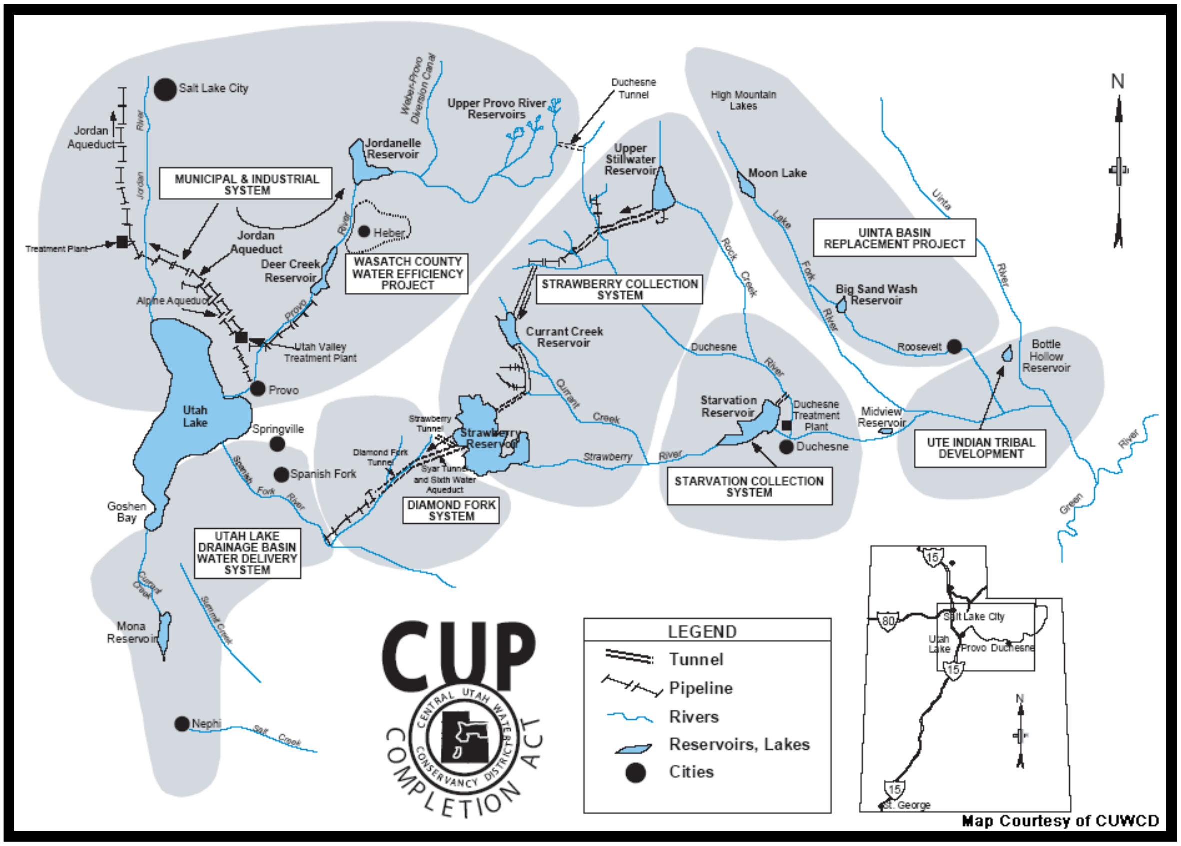

Figure 3-7. Central Utah Project – Bonneville Unit water management and diversion diagram. Source: Utah Reclamation Mitigation and Conservation Commission (https://www.mitigationcommission.gov/aboutus/aboutus_cup.html).

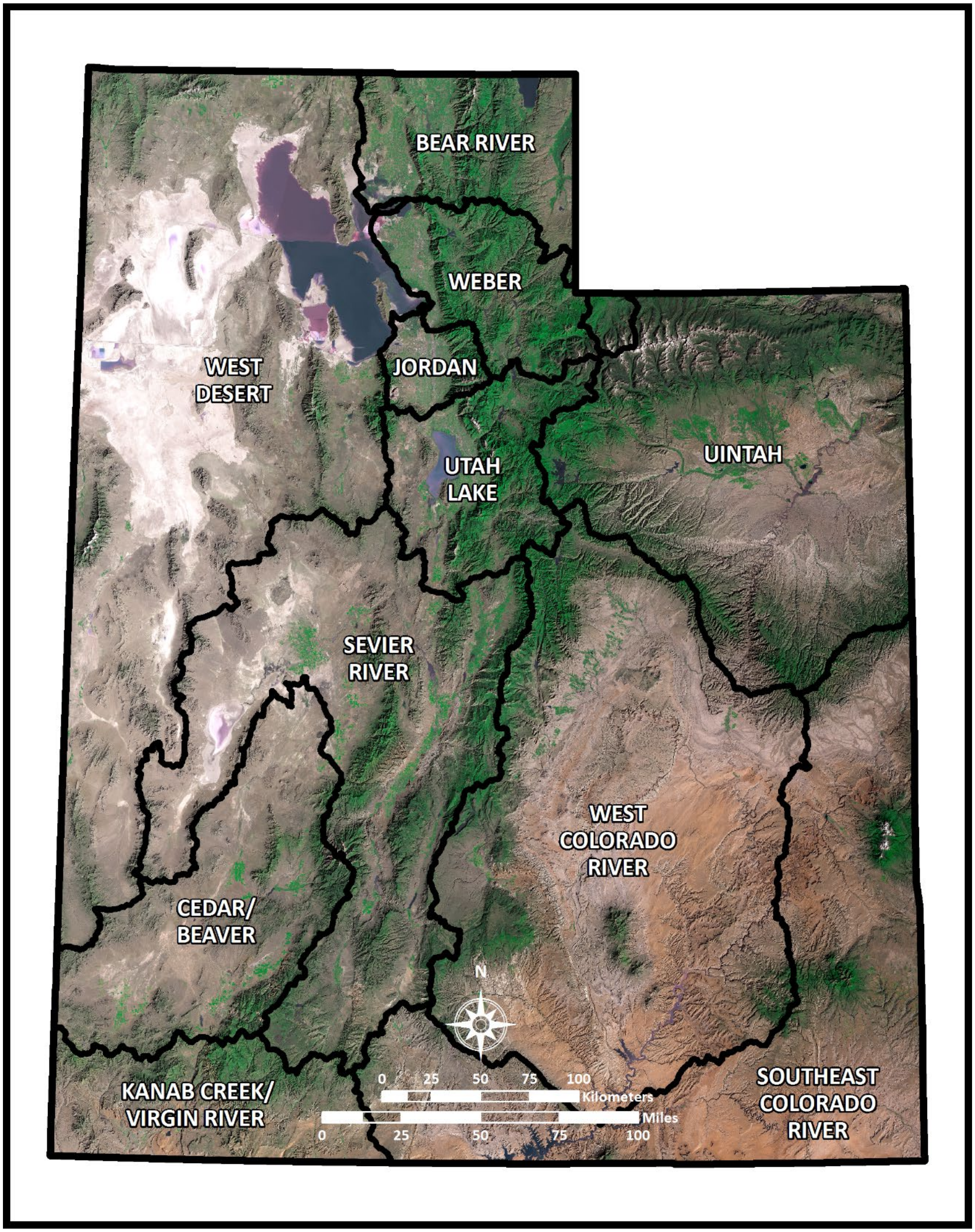

Figure 3-8. Watershed planning units as defined by the Utah Division of Water Resources for state water planning. Data source: Utah Division of Water Resources. Imagery source: United States Geological Survey Earth Explorer (https://earthexplorer.usgs.gov/). Landsat mosaic compiled by R. Douglas Ramsey.

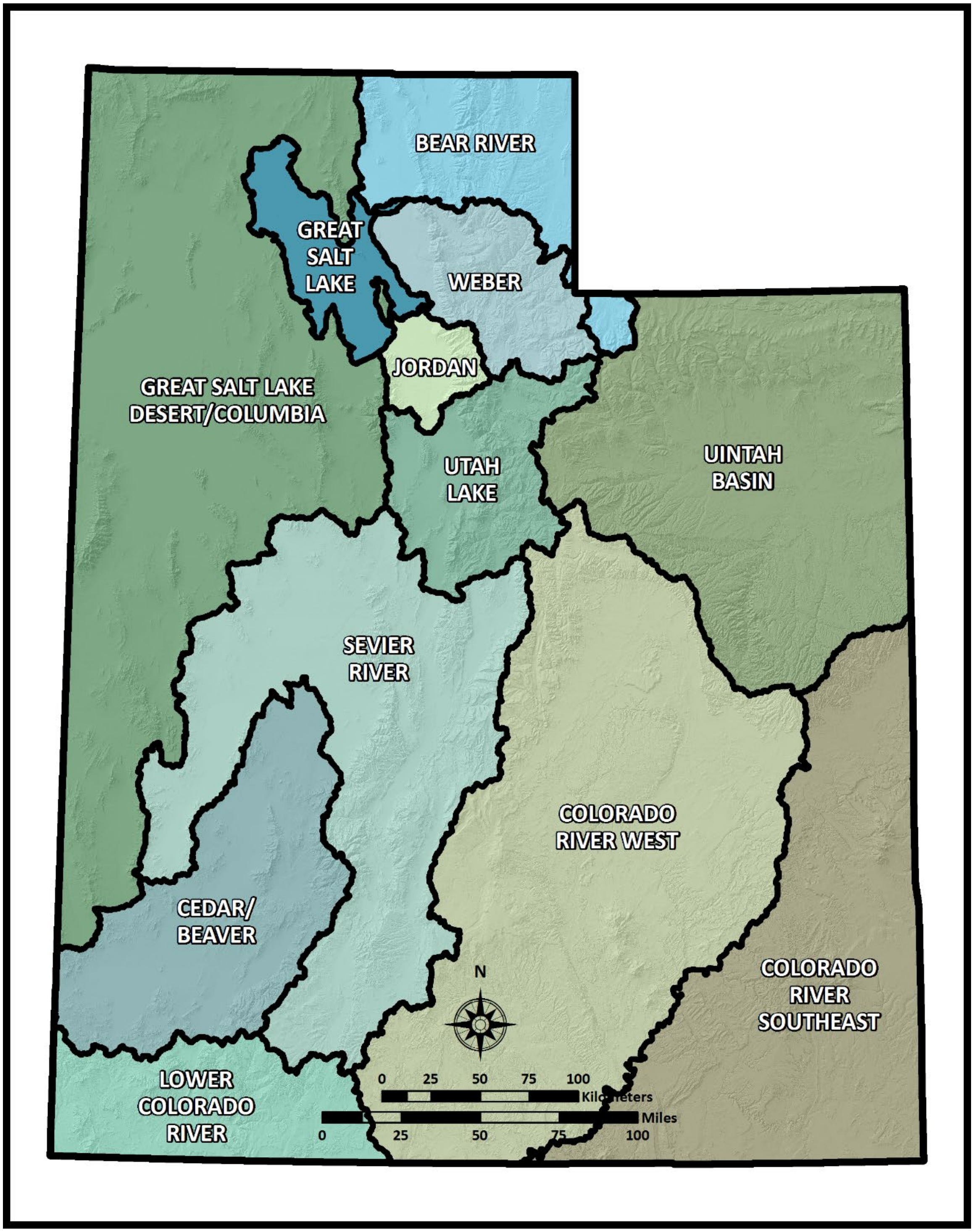

Figure 3-9. Watershed management units as defined by the Utah Division of Water Quality for water quality management. Data source: Utah Division of Water Quality (Watershed Protection Section).

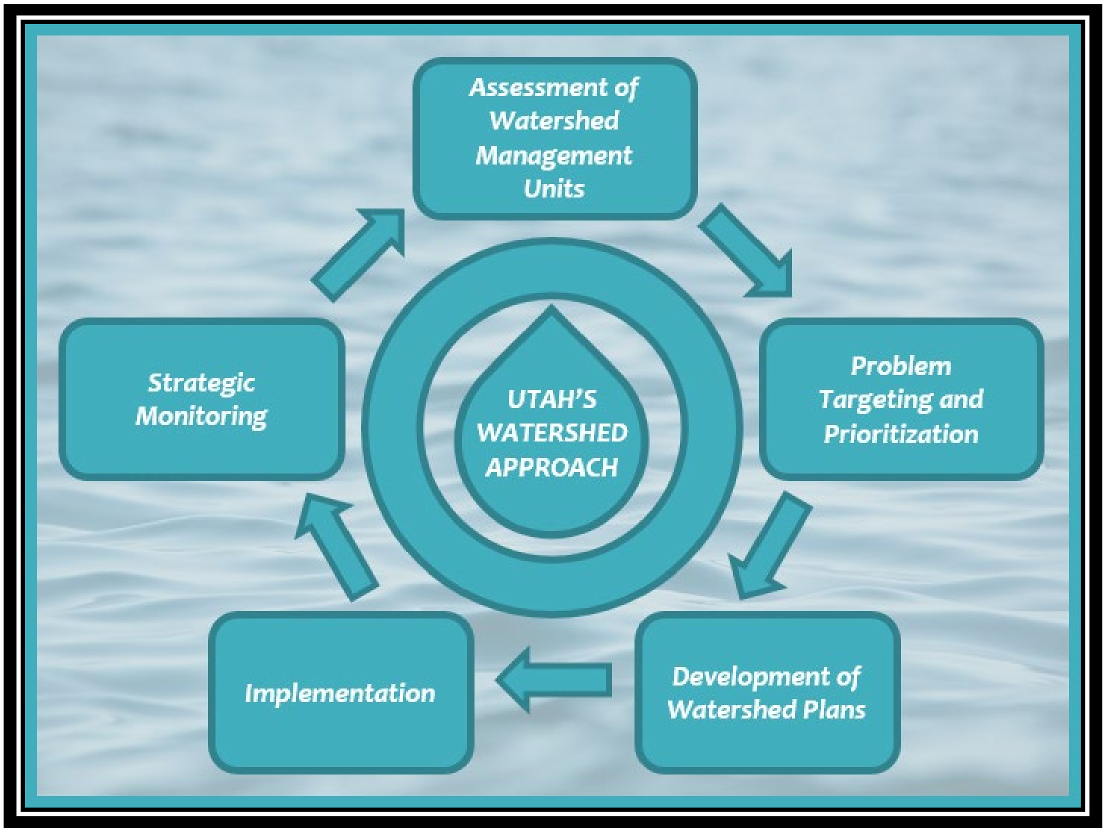

Figure 3-10. Utah's Watershed Approach. Adapted from UDEQ, 2013.

CHAPTER 4

A GEOGRAPHIC OBJECT-BASED IMAGE CLASSIFICATION OF THREE WATERSHED SUB-BASINS IN NORTHERN UTAH: METHODS, QUANTIFICATIONS, AND IMPLICATIONS

Introduction

Geospatial technologies, including geographic information systems (GIS) and remote sensing, have had a profound impact on contemporary planning practices. They have increasingly provided planners from a range of fields with effective tools that facilitate informed and up-to-date decisions in dynamic and multidimensional environments. Remote sensing, a geospatial science and technology concerned with the collection, observation, and measurement of the surface of the Earth through satellite and aerial imagery, has long been regarded as an integral tool for understanding physical processes and patterns and for supporting planning and monitoring efforts (Xiao and Zhan, 2009).

Remotely-sensed data, acquired from different sensors on various satellite and aerial platforms, are available in a wide range of temporal, spatial, and spectral resolutions. Coarse-resolution data support global and national analyses, while high-resolution data enable detailed assessments of local and regional landscapes. Remote sensing image interpretation techniques, including pixel-based and object-based approaches, provide effective and practical solutions for developing land use and land cover (LULC) information. Through the development of LULC information, inventories can be generated, the spatial arrangements of landscapes can be assessed, and environmental parameters can be quantified. Multi-temporal analyses can provide an additional perspective on the evolution of environments.

Project Objectives

The Remote Sensing/GIS Laboratory at Utah State University received a United States Environmental Protection Agency (USEPA) Region 8 Wetland Program Development Grant. Wetland Program Development Grants provide state, tribal, and local government agencies with the resources to build and enhance programs that protect, manage, and restore wetlands; and to conduct projects and research that promote improved understanding of the causes, effects, and prevention of water pollution (USEPA, 2016). The primary objective of this specific Wetland Program Development Grant was to develop a high-resolution, spatially accurate impervious surface land cover dataset for three urban sub-basins in northern Utah – Lower Bear-Malad, Lower Weber, and Jordan – using geographic object-based image analysis (OBIA). The secondary objective of the grant was to calculate watershed-scale quantifications of imperviousness for the three sub-basins using the impervious surface land cover dataset. These two objectives were identified as a means to support integrated water resources planning and management in northern Utah. Specifically, these objectives support Utah's Wetland Program Plan (WPP), contribute to Utah's Watershed Approach to managing nonpoint source pollution, and provide general assessments of the watershed condition in northern Utah.

Within Utah's WPP, there are several objectives and action items enumerated. Many of these items are attained or supported by the development of a high-resolution impervious surface land cover dataset. An impervious surface land cover datasets can (1) serve as an indicators of cumulative stress from urbanization, (2) support the development of ecologically relevant and scientifically defensible metrics that can be integrated into watershed health and wetland condition assessments, (3) provide general assessments of watershed and wetland condition within or near urban areas, (4) support the identification of thresholds of imperviousness that could predict watershed impairment, and (5) support the identification of sites in need of restoration or protection (Hooker and Jones, 2013).

In addition to the first two objectives, a third objective, which was not outlined in the USEPA grant proposal, was identified during the initial phase of the project. This objective extended beyond the original scope of the project and included the development of comprehensive LULC classifications in which the entirety of the three sub-basins would be interpreted. Therefore, in addition to developing an impervious surface land cover dataset, it was determined that several other LULC types would be delineated during the modeling process. The motivation for improving upon the original objective was to provide a more valuable and functional dataset for other agency, municipal, or private planning efforts in the state of Utah, whether local or regional in scale.

Literature Review

Urban LULC information has been identified as a central component in evaluating and monitoring natural resources and for guiding planning and decision-making activities in cities and urbanizing regions (Devi and Baboo, 2012). Remote sensing technology and image interpretation techniques have provided land managers, city and regional planners, decision-makers, and scientists with valuable tools that enable the development of accurate, up-to-date, and spatially explicit information (Yang et al., 2003). In urban environments, impervious surfaces are the predominant land cover type and they have been associated with a variety of hydrological and aquatic impacts. Impervious surface land cover datasets have been recognized as a key indicator in assessing urban environments in that they can provide an improved understanding of urban growth patterns and processes; they can contribute to the assessment of the hydrological and aquatic issues; and they can be incorporated into hydrologic models to develop implementation strategies that improve watershed health, wetland condition, and stormwater management. Impervious surface land cover datasets have been generated using an assortment of remotely-sensed data and remote sensing image interpretation techniques. However, there is a growing recognition that high-resolution LULC datasets, which are developed using OBIA techniques, provide more information and value to local and regional planners and decision-makers due to the improved spatial resolution and higher levels of accuracy.

Impervious Surfaces

Definition of Impervious Surfaces

Impervious surfaces are one of the most widespread land cover types in urban and suburban environments (Yang et al., 2003). They represent the imprint of urbanization and land development on the landscape (Schueler, 1994). They are constructed surfaces that are directly related to human activity and are typically composed of asphalt and concrete (Barnes et al., 2002; Slonecker et al., 2001).

Impervious surfaces can be divided into two general categories: (1) the transport system, which includes roads, parking lots, driveways, and sidewalks, and (2) rooftops, which includes residential, commercial, industrial, and institutional buildings and structures. The transport system often exceeds the rooftop component in terms of total imperviousness (Schueler, 1994).

Impacts of Impervious Surfaces

Impervious surfaces impose a variety of hydrologic, physical, chemical, and biological changes within a watershed (Booth and Jackson, 1997; Flinker, 2010). Impervious surfaces disrupt the natural hydrologic cycle by effectively sealing surfaces, repelling water, and preventing precipitation and meltwater from infiltrating soils (Schiff and Benoit, 2007; Barnes et al., 2002). As the area of impervious surfaces increases, the velocity and volume of surface runoff increases, often dramatically increasing peak discharges associated with storm and snowmelt events. With an increase in runoff and an increase in hydrologic activity, there is a corresponding decrease in infiltration (Figure 4-1). The reduction in infiltration increases the probability and severity of flooding, decreases groundwater recharge, and lowers water tables. Decreased groundwater supplies and lower water tables often reduce the interflow and baseflow groundwater contributions to stream flows, which can result in intermittent or dry stream beds during low flow periods (Arnolds and Gibbons, 1996; Barnes et al., 2002). Hydrologic changes can have large and immediate effects on the physical condition of wetlands. Increased runoff can alter wetland depth, duration, and frequency of inundation. Diminished infiltration in wetland watersheds can also reduce stream baseflows and groundwater supplies to wetlands (Reinelt et al., 1998).

Changes in watershed hydrology give rise to an array of physical impacts. Enhanced runoff accelerates streambank erosion, which increases sediment yields, decreases channel and bank stability, alters stream bed composition and morphology, and impacts sedimentation regimes in wetlands (Barnes et al., 2002; Reinelt et al., 1998). An increase in erosion often results in wider and straighter stream channels with a significant loss in streamside vegetation (Arnold and Gibbons, 1996). The loss of vegetative cover leads to greater water temperature fluctuations. Water temperatures fluctuations are often intensified by the contribution of warm runoff from impervious surfaces (Slonecker et al., 2001).

An increase in impervious surfaces yields significant changes in water chemistry and quality. More intensive land uses, such as urban development, generate more pollutants. Consequently, urban runoff is often the primary cause of significant local and regional nonpoint source pollution (Arnold and Gibbons, 1996; Barnes et al., 2002). A variety of pollutants (i.e. nutrients, bacteria, and organic matter), heavy metals, and hydrocarbons collect on impervious surfaces. During precipitation and stormwater runoff events, impervious surfaces serve as an efficient conveyance system for transporting and discharging these pollutants and sediments into waterways and wetlands (Arnold and Gibbons, 1996). Excess nutrients, such as nitrogen and phosphorus, can lead to nutrient enrichment, thus stressing aquatic systems and influencing vegetation dynamics and composition. Heavy metals and hydrocarbons transported in stormwater runoff accumulate in wetland sediments, resulting in potential groundwater contamination and toxicity and bioaccumulation in aquatic organisms and plants (Wright et al., 2006).

Changes in hydrology, physical in-stream characteristics, and chemical composition due to impervious surfaces result in substantial modifications to biological systems. Characteristics, such as increased flow volume, pollutant runoff, and fluctuations in temperature, adversely affect aquatic and terrestrial ecosystems, habitat, biological diversity, and primary productivity (Slonecker et al., 2001; Reinelt et al., 1998). Populations of naturally occurring and environmentally sensitive organisms decline and are gradually replaced by species more tolerant of degraded conditions. Macroinvertebrate, fish, and amphibian diversity is reduced, and the health and abundance of riparian and wetland plants deteriorate, lessening shading and microhabitats (Barnes et al., 2002; Flinker, 2010). These impacts eventually translate into long-term shifts in plant and animal communities (Reinelt et al., 1998).

Impervious Surface Area as an Environmental Indicator

Impervious surface land cover datasets can support a wide range of urban ecosystem studies, including urban hydrology, urban climatology, land use planning, natural resource planning and management, and environmental monitoring (Yang et al., 2003; Zhou and Wang, 2006). One of the most basic applications of an impervious surface land cover dataset is its use as an index of urban growth and intensity at watershed, regional, and national scales (Schueler et al., 2009). However, within recent decades, impervious surface land cover datasets have become increasingly important and prevalent for assessing and addressing the impacts of urbanization on water resources and aquatic ecosystems.

Impervious surface area and percent imperviousness have emerged as key indicators and predictors of watershed condition (Arentsen et al., 2004; Zhou and Wang, 2006), and they have unique properties as watershed metrics in that they can be measured, tracked, and forecasted (Schueler et al., 2009). According to Arnold and Gibbons (1996), development of an impervious surface land cover dataset may often be the most feasible and cost-effective approach for addressing water pollution, especially in locations where there is limited information on pollutant loadings, hydrologic modeling, and management practices. Additionally, an impervious surface land cover dataset has two components that make it valuable as an environmental indicator. First, it is integrative, suggesting that it can estimate or predict cumulative water resource impacts without regard to specific factors, and second, it is measurable, suggesting that it can be quantified for use in planning and regulatory applications.

Thresholds of Impervious Surfaces

Monitoring and modeling studies have frequently demonstrated that the percentage of impervious surfaces is directly related to select water quality parameters, aquatic ecosystem function, urban pollutant loads, and overall watershed health (Schueler, 1994; Civco et al., 2006; Booth and Reinelt, 1993; Brabec et al., 2002). Specific studies have investigated the thresholds of imperviousness at which various watershed functions begin to decline. For instance, Klein (1979) reported that stream quality impairments are first evidenced when watershed imperviousness reaches 12 percent, but does not become severe until imperviousness reaches 30 percent. Booth and Jackson (1997) observed that aquatic system function declines at 10 percent impervious area. Holland et al. (2004) noted that adverse changes in the physical and chemical environment (i.e. altered hydrography, changes in salinity variance, altered sediment characteristics, increased chemical contaminants, and increased fecal coliform loadings) were observed when impervious cover exceeded 10 to 20 percent. Hicks (1995) noted a well-defined inverse relationship between freshwater wetland habitat quality and impervious surface area, whereby wetland function deterioration was observed when impervious cover exceeded 10 percent.

Based on a meta-analysis of impervious surface thresholds, Schueler (1994) developed an Impervious Cover Model (ICM). The ICM is based on the average percentages of impervious cover at which watershed functions begin to decline. It classifies urban streams into four management categories: sensitive streams (1-10 percent impervious cover), impacted streams (10-25 percent impervious cover), non-supporting streams (25-60 percent impervious cover), and urban drainages (60-100 percent impervious cover) (Figure 4-2). These categories suggest that degradation (i.e. stream bank instability and loss of biodiversity) occur at relatively low levels, generally beginning at 10 percent impervious cover (Schueler, 1994; CWP, 2003; Arnold and Gibbons, 1996).

In 2009, the ICM was strengthened and reformulated to reflect more recent research. The reformulated model suggests that sharply defined impervious cover thresholds are rare, and that most regions show a generally continuous but variable gradient of stream degradation as impervious cover increases. The reformulated model expresses transitions between stream quality classifications instead of distinct breaks, whereby 5 to 10 percent impervious cover represents the transition from sensitive to impacted streams, 20 to 25 percent impervious cover represents the transition from impacted to non-supporting streams, and 60 to 70 percent impervious cover represents the transition from non-supporting streams to urban drainages (Schueler et al., 2009) (Figure 4-3).

Although threshold values of imperviousness may be debatable and may have some limitations, the thresholds of initial degradation are fairly consistent throughout the literature (Arnold and Gibbons, 1996). Threshold values, as well as the reformulated ICM, can provide watershed planners, water quality scientists, and policy makers with a reasonable foundation for identifying an appropriate time to initiate a regulatory response (Booth and Jackson, 1997). Additionally, threshold values can support water quality objectives, stormwater practices, land use controls, and monitoring and restoration efforts (Schueler, 1994; Schueler et al., 2009).

Land Use and Land Cover Classification Methods

Land cover refers to the observed physical cover on the surface of the Earth, such as vegetation, impervious surfaces, or water. Land use refers to the activities on the land and the social purpose that the land serves, such as timber production, urban or suburban development, agriculture, or recreation. Land cover information can be interpreted and classified based on direct observation; however, land use is generally inferred based on the associated land cover (Nielsen, 2014; Bibby and Shepherd, 1999). While there are distinct differences between land cover and land use, the majority of image classification systems and schemes encompass some combination of the two categories. With a classification system or scheme providing a structure for image interpretation and classification, LULC information are extracted from satellite and aerial images using a variety of methods. The goal of these methods is to group and categorize image data into meaningful thematic classes. This categorization is principally based on the premise that different features have distinguishable and separate spectral and spatial characteristics (Arthur et al., 2000; Aronoff, 2005; Horning, 2004).

Traditional Image Classification

Numerous image interpretation and classification methods have been developed to extract LULC information from remotely-sensed imagery. Manual photo-interpretation is a longstanding technique for extracting LULC information from aerial photographs and imagery. Manual interpretation relies on human analysts who can classify an image into discrete features based on differences in tone, texture, shape, pattern, and relationship to other objects (Horning, 2004). While manual interpretation is effective and accurate, it is time consuming, labor intensive, and cost prohibitive (Blundell and Opitz, 2006).

Advances in digital remote sensing science and technology have provided more expedient and cost-effective methods for classifying LULC information, particularly at global, regional, and watershed basin scales (Sleavin et al., 2000). Two fundamental approaches have been developed for extracting information from digital images: supervised and unsupervised image classification. In supervised image classification, the analyst defines areas, or groups of pixels, in the image that are representative of each LULC class of interest. These areas are used to define signatures for each class which can then be applied to an entire image using one of several classification algorithms (Aronoff, 2005). In unsupervised image classification, no prior knowledge about the characteristics and distribution of LULC classes is required. Instead, the classes are defined using statistical algorithms that cluster spectrally-similar pixels. The spectrally-similar clusters are subsequently assigned to LULC classes (Cihlar, 2000).

Although supervised and unsupervised classification methods are widely used, they have some limitations. With these traditional methods, the results are strictly based on the spectral characteristics of individual pixels; therefore, categorical data with hard boundaries are generated because each pixel can be assigned to only one class (Aronoff, 2005). This is problematic with medium- and coarse-resolution imagery because pixels are frequently composed of different LULC types, or spectral signatures (Weng, 2012). This issue, commonly referred to as the mixed pixel problem, is prevalent in urban landscapes because there may be several small and spectrally distinct features, such as buildings, roads, trees, grass, water, and soil, that contribute to one pixel value (Slonecker et al., 2001).

Consequently, numerous improved methods, such as fuzzy classification and spectral mixture analysis, have been developed to resolve some of the limitations of traditional pixel-based approaches and have permitted the derivation of LULC information at the subpixel level in medium- and coarse-resolution data (Aronoff, 2005; Yang, 2006). While these methods are innovative and have been valuable in conducting global, national, and regional studies and assessments, they are not suited for detailed LULC studies or high-resolution imagery. When traditional pixel-based classification approaches are applied to high-resolution imagery, single pixels no longer capture the characteristics of features, and the intra-class spectral variability increases. This variability reduces the statistical distinction between classes and results in individual pixels being classified differently than neighbors. The output is frequently a pixelated representation of LULC (exhibiting the so-called salt-and-pepper effect) with reduced levels of accuracy (Yu et al., 2006; Bock et al., 2005).

Object-Based Image Analysis

The incompatibility between traditional classification methods and advances in remote sensing science, such as improved sensor technology and increasing spatial resolutions, prompted the geospatial science community to develop a new approach for deriving information from high-resolution imagery more efficiently and precisely (Blaschke, 2010; O'Neil-Dunne et al., 2009). Additionally, a rapidly growing demand for detailed and spatially explicit LULC information propelled the advancement of new methods (Bock et al., 2005). Consequently, OBIA emerged as a result of integrating geospatial concepts and advanced image analysis techniques (Lang, 2008). OBIA is a relatively new technique, becoming a research topic around the year 2000, coinciding with the release of the first commercially-available software program, eCognition (Blaschke, 2010). OBIA utilizes a combination of both geospatial and image processing methods to extract meaningful information from high-resolution imagery (Lang, 2008). OBIA has been defined as a sub-discipline of Geographic Information Science (GIScience) devoted to developing automated methods to partition remote sensing imagery into meaningful image objects, and assessing their characteristics through spatial, spectral, and temporal scales (Hay and Castilla, 2006).

The primary objectives of OBIA are to overcome the limitations of traditional pixel-based methods, and to sufficiently replicate human interpretation of remotely-sensed images in semi-automated way that result in increased repeatability and decreased subjectivity and expense (Hay and Castilla, 2006). Whereas traditional remote sensing classification methods solely rely on the spectral information of single pixels as the basis of categorization, OBIA relies on the spectral, spatial, textural, and contextual information of groups of pixels, or image objects (Blaschke and Lang, 2006; Xiaoxia et al., 2005).

In OBIA software programs, a process called segmentation is used to group spectrally and/or texturally similar pixels of an image into image objects. Segmentation is an efficient means of partitioning remotely-sensed imagery into meaningful objects and it is useful for aggregating the high levels of detail contained within high-resolution imagery (Lang, 2008) (Figure 4-4). The change of classification units from pixels to image objects, or segments, reduces the intra-class spectral variation (or heterogeneity), thus minimizing or removing the salt-and-pepper effect that is common with pixel-based methods (Liu and Xia, 2010). Segmentation is an important foundation for subsequent classification because all object features are dependent on the objects derived from this process (Yu et al., 2006).

Once a remotely-sensed image is segmented into meaningful image objects, a set of knowledge-based classification rules are defined in order to assign each segment to a specified class (Xiaoxia et al., 2005). Specifically, rules about object properties, such as segment geometry, tone, texture, and contextual associations, are applied to classify the segments of the image (Addink et al., 2012) (Figure 4-5). Segment geometry is a combination of shape and size; tone indicates the spectral properties of an individual band; texture refers to the frequencies of change in tones and their resulting spatial arrangements; and contextual associations refer to relationships with neighboring image objects (Blaschke et al., 2014; Weng, 2012).

Object-Based Image Analysis Studies

Object-based techniques have been implemented in numerous studies at various scales. Blaschke (2010) conducted a detailed review of OBIA literature which revealed that object-based techniques are being widely used in numerous scientific disciplines. OBIA has been widely used in ecological studies to map habitats and land cover. For instance, Bock et al. (2005) suggested that object-based classification methods are valuable for habitat mapping at a range of different scales. Conchedda et al. (2008) successfully utilized object-based methods to map the land cover of a mangrove ecosystem in Senegal, Africa. Stow et al. (2008) and Laliberte et al. (2004) revealed that object-based approaches are valuable for monitoring shrubland habitat change. Vanderzanden and Morrison (2002) indicated that Feature Analyst, an OBIA software program, was highly successful at mapping four different forest cover types. Walker and Briggs (2007) conducted a study in which object-based methods were adopted in order to delineate woody vegetation in an arid urban ecosystem. Platt and Schoennagel (2009) used an object-based approach to assess changes in tree cover in the Colorado Front Range from 1938 to 1999. Pascual et al. (2008) presented an approach for characterizing Scots pine stands in forests using OBIA and a digital canopy height model derived from airborne light detection and ranging (LiDAR) data.

Object-based techniques have also been extensively used in urban studies to map urban features, such as impervious surfaces and urban tree canopy cover. For instance, Reveshty and Rabet (2012) used an object-based approach applied to QuickBird imagery to support the development of urban land use maps for urban planning and management in Zanjan City, Iran. Myint et al. (2011) established that object-based classifiers produced a significantly higher overall accuracy as compared to maximum likelihood classifiers when mapping urban land cover from QuickBird imagery in Phoenix, Arizona. Moskal et al. (2011) confirmed that an object-based approach applied to NAIP (National Agriculture Imagery Program) aerial imagery was suitable for developing repeatable and accurate urban tree canopy cover assessments in Seattle, Washington. Doxani et al. (2008) demonstrated that object-based analysis of multi-temporal QuickBird and Ikonos imagery was an effective technique for monitoring land cover changes in the urban environment of Thessaloniki, Greece. Durieux et al. (2008) revealed that an object-based classification methodology applied to SPOT 5 (Satellites Pour l'Observation de la Terre) satellite imagery was a valuable approach for monitoring urban sprawl in the French oceanic island of Le Réunion. Zhou and Troy (2008) presented an object-based approach for analyzing and characterizing the urban landscape structure at the parcel level in Baltimore, Maryland, using Emerge Digital Aerial Imagery and LiDAR data. Chen et al. (2007) demonstrated the potential of using an object-based approach to map urban land cover for the city of Beijing, China, from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) imagery.

Study Area

The study area is composed of three 8-digit hydrologic unit code (HUC) sub-basins in northern Utah. From north to south, the three sub-basins include Lower Bear-Malad (HUC 16010204), Lower Weber (HUC 16020102), and Jordan (HUC 16020204). The Lower Bear-Malad sub-basin extends into Idaho; however, it was subset to the state of Utah per the requirements of the USEPA Wetland Program Development Grant Proposal (Figure 4-6). The Lower Bear-Malad sub-basin is 1,934 square kilometers (747 square miles); the Lower Weber sub-basin is 3,420 square kilometers (1,320 square miles); and the Jordan sub-basin is 2,106 square miles (813 square miles). Collectively, the study area is 7,460 square kilometers (2,880 square miles).

The study area encompasses land from eight counties. Lower Bear-Malad encompasses land from Box Elder and Cache counties; Lower Weber encompasses land from Weber, Davis, Morgan, Box Elder, and Summit counties; and Jordan encompasses land from Salt Lake, Davis, and Tooele counties. Within the three sub-basin, land ownership is composed of private, federal (i.e. Bureau of Land Management, United States Forest Service, United States Fish and Wildlife Service, Department of Defense, Army Corp of Engineers, and Bureau of Reclamation), and state land (i.e. state sovereign land, wildlife reserve/management areas, parks and recreation, and state trust land) (Figure 4-7). Private land ownership comprises 73.7 percent; federal land ownership comprises 18.2 percent; and state land ownership comprises 8.1 percent.

The three sub-basins encompass the eastern shores and wetlands of the Great Salt Lake, span the northern two-thirds of the highly urbanized Wasatch Front, and include portions of the Wellsville Mountains, Northern Wasatch Range, and Central Wasatch Range. There are three primary river systems within the study area – the Bear River, Weber River, and Jordan River. The Bear River drains the Bear River Range and Wellsville Mountains, as well as the northern slopes of the Uinta Mountains. The Weber and Ogden rivers, which merge on a delta on the eastern shores of the Great Salt Lake, drain the Northern Wasatch Range. The Jordan River drains the Central Wasatch Range and the southwestern slope of the Uinta Mountains via the Provo River (Waddell et al., 2009). These three river systems provide the majority of freshwater inflow into the Great Salt Lake (UDWQ, 2009) (Figure 4-8).

The Great Salt Lake is the fourth largest terminal lake in the world and the largest salt water lake in the Western Hemisphere (Arnow and Stephens, 1990). The Great Salt Lake and freshwater inflows from the Bear, Weber, and Jordan rivers support extensive permanent and seasonal wetlands on the margins of the lake. The Great Salt Lake Wetlands include an estimated 1,728 square kilometers (427,000 acres) and represent 75 percent of the wetlands in Utah (UDWQ, 2009). The Great Salt Lake Wetlands provide a mosaic of unique ecological communities including freshwater and ephemeral ponds, brackish marshes, mudflats, playas, salt flats, and open salt water. Approximately 250 species of birds occur within the Great Salt Lake Ecosystem, of which 83 species are waterbirds. The Great Salt Lake Ecosystem is vitally important to several species and has been internationally and globally recognized as critical habitat and as a migrational corridor for waterbirds (DuFault et al., 2000). In recognition of its significance, the Great Salt Lake Ecosystem was designated as a Hemispheric Reserve in the Western Hemisphere Shorebird Reserve Network in 1992 (Waddell et al., 2009).

Management, conservation, and restoration efforts have been made to protect and restore the Great Salt Lake Ecosystem. The Bear River Migratory Bird Refuge, preserves and reserves, such as the Great Salt Lake Shorelands Preserve, and several Utah Division of Wildlife (UDWR) waterfowl management areas (WMAs) protect vitally important wetlands. However, urban and industrial development continue to threaten and stress the aquatic ecosystems within the Wasatch Front and the Great Salt Lake Ecosystem. Specifically, the hydrology and water quality of these ecosystems have been altered by industrial and urban development as a result of surface- and ground-water withdrawal, excessive pollution, high rates of nutrient loading, and invasive species expansion (UDWQ, 2012).

Three of the most urban counties in the state of Utah (i.e. Salt Lake, Davis, and Weber counties) border the Great Salt Lake and include 57 percent of Utah's population. Within the three sub-basins, there are 63 municipalities (Figure 4-9). Fifty-eight of the municipalities are located on the valley floors and foothills of the Wasatch Front. The remaining five municipalities are back valley or ski resort communities. The estimated population within the incorporated areas is 1.5 million people. Brigham City is the largest municipality within the Lower Bear-Malad sub-basin, with an estimated population of 17,899; Ogden is the largest municipality within the Lower Weber sub-basin, with an estimated population of 82,825; and Salt Lake City is the largest municipality within the Jordan sub-basin, with an estimated population of 186,440 (USCB, 2010).

Utah was recently identified as the fastest growing state in the nation, with several Utah counties recently being listed among the top 10 fastest growing counties. This growth is expected to continue, and it is estimated that the population will increase anywhere from one million to two-and-a-half million by the year 2050. The majority of this growth will occur within the counties of the Wasatch Front (i.e. Salt Lake, Davis, Utah, and Weber). Existing large population centers are expected to expand; however, slower rates of growth will likely occur in Salt Lake and Davis counties due to the limited amount of developable land (Utah Foundation, 2014). This growth will have profound impacts on the ecological, biological, and chemical integrity of aquatic ecosystems if not prudently managed and evaluated.

Data and Methods

Trimble eCognition

There are several commercial and open source OBIA software programs. Feature Analyst by Textron Systems, ENVI Feature Extraction by Harris Geospatial Solutions, and eCognition by Trimble are some of the more common commercial software packages. Although all three software programs have been successfully used to extract features from remotely-sensed imagery, previous evaluations conducted by Leydsman et al. (2008) and Leydsman-McGinty and Lowry (2010) suggested that Feature Analyst and ENVI Feature Analyst had limitations, specifically in terms of analyzing large data sets and producing models with high accuracy. Therefore, Trimble eCognition was identified as the most viable option for detailed LULC mapping based on processing capabilities, versatility, and levels of accuracy.

Trimble eCognition became the first commercially available OBIA software program when it was released by Definiens in 2000. In 2010, Trimble acquired Definiens' Earth Sciences Division, including eCognition software. eCognition has become the leading OBIA software program for data providers, remote sensing professional, and university researchers. It is an advanced and comprehensive image analysis software package that integrates a variety of geospatial data sets, including satellite and aerial imagery, LiDAR point clouds, and raster and vector data. eCognition facilitates the analysis of satellite and aerial imagery, with a range of spectral and spatial resolutions, through a suite of robust spectral-, spatial-, and context-based algorithms.

There are three Trimble eCognition software packages: eCognition Architect, eCognition Developer, and eCognition Server. eCognition Architect enables non-technical professionals to configure, calibrate, and execute semi-automated image analysis workflows. eCognition Developer is a powerful development environment for OBIA whereby rule sets are developed for the analysis of remotely-sensed data. eCognition Server provides a processing environment for batch execution of image analysis (Trimble, 2016). eCognition Developer and eCognition Server were used in this analysis.

eCognition provides an iterative, yet structured, workflow that entails data integration, image segmentation, rule set development, image classification, and rule set refinement. First, imagery and thematic data, which are generally processed in an outside software package, such as Esri ArcGIS, ERDAS IMAGINE, or Quick Terrain Modeler, are loaded into eCognition. Second, by defining a series of parameters in eCognition, such as image layer weights, scale parameter, shape, and compactness, the image is segmented into image objects, or groups of similar pixels. Third, once an image is segmented into meaningful image objects, rules based on spectral, spatial, textural, and contextual properties are developed in order to classify the image objects into discrete objects. Image segmentations and rule sets are frequently refined, and sometimes reconfigured, to produce the most optimal classification results.

Geospatial Data

The data selected for use in this analysis include the Watershed Boundary Dataset (WBD), NAIP aerial imagery, Water Related Land Use (WRLU) data, road centerline data, stream data, soils data, and National Elevation Dataset (NED) data. All data were downloaded from state and federal agency websites and were projected to North American Datum (NAD) 1983 Universal Transverse Mercator (UTM) Zone 12 North.

The WBD was downloaded from the United States Geological Survey (USGS) National Map Hydrography Viewer (https://viewer.nationalmap.gov/basic/). The

WBD, which represents drainage basins as enclosed areas, is a hierarchical system of hydrologic units. Each hydrologic unit is identified by a unique HUC consisting of two to 12 digits based on the level of classification in the hydrologic unit system. Regions (HUC 2) are the largest units, whereas sub-watersheds (HUC 12) are the smallest units. Sub-basins (HUC 8) and watersheds (HUC 10) were used in this analysis. The three sub-basins – Lower Bear-Malad, Lower Weber, and Jordan – and the watersheds comprising the three sub-basins were extracted from the WBD. The Lower Bear-Malad sub-basin was subset to the state of Utah per the requirements of the USEPA Wetland Program Development Grant Proposal. The three sub-basins were buffered by one kilometer to reduce the influence of edge pixel values when conducting the spatial analyses. The watershed and sub-watershed boundaries were reserved for conducting the watershed-scale quantifications subsequent to generating the LULC classification.

NAIP aerial imagery flown and collected in the summer of 2011 was downloaded from the Utah Automated Geographic Reference Center (AGRC, https://gis.utah.gov/). NAIP aerial imagery is acquired during the agricultural growing season under the direction of the United States Department of Agriculture (USDA) Farm Service Agency. It is acquired at a one-meter ground sample distance within a horizontal accuracy that matches within six meters of photo-identifiable ground control points (USDA, 2011). The spectral resolution of NAIP aerial imagery is natural color, meaning there are red (R), green (G), and blue (B) bands. However, beginning in 2006, some states began to acquire an additional near infrared (NIR) band, making NAIP aerial imagery a four-band multispectral product. The addition of a NIR band provides for greater visual interpretation and digital analysis and enables the development of image indices (USDA, 2012). The 2011 four-band NAIP image tiles for the three sub-basins were opened in ERDAS IMAGINE, mosaicked to create image composites, and subset to the buffered sub-basin boundaries (Figure 4-10).

The WRLU data, road centerline data, stream data, and soils data were downloaded from the Utah AGRC. The WRLU data are published annually by the Utah Division of Water Resources to assist in the development and maintenance of the State Water Plan. These data include the types and extents of irrigated crops, dry land agriculture, wet and open areas, and residential and industrial areas (AGRC, 2016a). The road centerline dataset represents roads and highways in the state of Utah. The stream dataset, derived from the National Hydrography Dataset (NHD), represents stream segments or reaches that make up the surface water drainage system in Utah. The soils dataset, developed by the National Cooperative Soil Survey, represents the extent of defined soils types in Utah (AGRC, 2016b). The NED data, with a resolution of 1/3 arc-second (approximately 10 meters), were downloaded from the USGS National Map Viewer and mosaicked in Esri ArcGIS to create composites. The NED is a raster product that provides seamless elevation data for the United States for use in earth science studies and mapping applications (USGS, 2016).

Rule Set Development

The Jordan sub-basin was selected as the first area of analysis because it is the most urbanized of the three sub-basins. NAIP aerial imagery for the Jordan sub-basin was loaded into eCognition and a subset of the image was defined to begin rule set development. The image was segmented into image objects using the multiresolution segmentation (Figure 4-10). This segmentation algorithm is a bottom-up region merging technique that considers each pixel as a separate object and subsequently merges similar image objects to form larger segments (Rahman and Saha, 2008). The multiresolution segmentation algorithm minimizes average heterogeneity and maximizes homogeneity. This algorithm is suitable for extracting features that are characterized not solely by color but also by shape (Trimble, 2014).

The parameters within the multiresolution segmentation algorithm – image layer weights, scale parameter, shape, and compactness – were adjusted and evaluated to determine the most suitable segmentation. The image layer weights parameter enables individual weights to be assigned to each image band to account for variations in their relative importance (Hamilton et al., 2007). The scale parameter determines the size of the objects based on maximum heterogeneity, whereby a higher scale parameter yields larger objects. The shape criterion determines the degree of object shape in relation to spectral composition, whereby higher values result in objects more optimized for spatial homogeneity and lower values result in objects more optimized for spectral homogeneity (Trimble, 2014; Hamilton et al., 2007). The compactness criterion determines the closeness of pixels clustered in an object by comparing it to a circle, whereby higher values produce more compact image objects (Gupta and Bhadauria, 2014; Hamilton et al., 2007).

The multiresolution segmentation was subsequently refined by using the spectral difference segmentation algorithm (Figure 4-11). The spectral difference segmentation algorithm merges neighboring image objects into larger image objects based on mean spectral values. This algorithm is designed to refine existing segmentation results. As with the multiresolution segmentation algorithm, layer weights can be assigned based on importance or suitability (Trimble, 2014).

Subsequent to defining suitable segmentation parameters, a normalized difference vegetation index (NDVI) was calculated in eCognition as a customized object feature (Figure 4-12). Customized object features can be relational or arithmetic features. Relational features are used to compare a particular feature of one object to those of a related object. Arithmetic features are composed of existing features, variables, and constants (Trimble, 2014). The NDVI is an arithmetic feature that is derived from the red and near infrared bands using the formula [NDVI = (NIR-R)/(NIR+R)]. The NDVI is the most widely used image index in the processing of remotely-sensed data (Myneni et al., 1995). The NDVI is frequently calculated as a measure of vegetation, whereby higher values represent increases in the quantity of green biomass (Burgan and Hartford, 1993) and lower values signify non-vegetated surfaces, such as water, barren areas, or impervious surfaces (Yuan and Bauer, 2007).

A preliminary rule set for classifying impervious surfaces was developed using three primary object features that were derived from the NAIP imagery: NDVI, Hue-Saturation-Intensity (HSI), and Ratio Blue. The HSI object feature is a transformation that converts RGB color values to hue (color), saturation, or intensity (brightness) based on maximum and minimum RGB values. Specifically, a NIR-R-B Hue object feature was created. The Blue Ratio is a pixel-based object feature that represents the amount that the blue band contributes to the total brightness (Trimble, 2014). For the three object features, appropriate threshold values were determined through an iterative process of adjusting values, executing rules, and viewing results.

The preliminary rule set was applied to a larger subset of the Jordan sub-basin and the results were evaluated. A qualitative assessment indicated that the rule set produced adequate results; however, there were some misclassification errors. These errors were largely confined to barren land, fallow agricultural fields, and sparsely vegetated foothills. These misclassification errors are common in many remote sensing studies due to the spectral similarity of these features (Flanagan and Civco, 2001). In fact, one of the primary challenges in accurately mapping impervious surfaces from four-band imagery, particularly in arid environments, is the lack of adequate spectral contrast between bare ground and impervious surfaces (Thomas et al., 2003; Crane et al., 2005).

As a result of these errors, it was determined that ancillary data sets should be incorporated into the eCognition rule set development process in order to improve classification accuracy. Incorporation of ancillary data sets would not only improve the classification accuracy of impervious surfaces, but would support the classification of other LULC classes. Therefore, during this initial phase of the project, it was determined that a wall-to-wall image classification with nine classes would be generated. A wall-to-wall image classification means that the entire image, or study area, is classified and that there are no geographic gaps or overlaps between classes. A wall-to-wall image classification was deemed beneficial for other state, municipal, and private planning efforts.

Using the Level I classes from the Anderson LULC Classification System as a guide (Anderson et al., 1976), nine general classes were identified for the three sub-basins: 1) agriculture (e.g. planted/cultivated/fallow fields); 2) barren/bedrock (e.g. playa, gravel pits, rocky outcrops, parcels slated for development); 3) impervious surfaces; 4) riparian/wetland; 5) snow; 6) sparse vegetation (e.g. semi-desert shrubland, senesced vegetation, herbaceous/invasive); 7) urban parks (e.g. parks/fields, golf courses, cemeteries), 8) vegetation (e.g. forest, urban tree canopy, turf/grass), and 9) water (Table 4-1).

Based on the preliminary classification and the defined LULC classes, a thorough qualitative assessment of classification errors was conducted and a review of existing statewide data sets was performed. The review revealed that WRLU data, road centerline data, stream data, soils data, and NED data would provide improvement to model results and would support the development of the wall-to-wall image classification. The data sets were opened in Esri ArcGIS, reprojected to NAD 1983 UTM Zone 12 North, if required, and subset to the buffered sub-basin boundaries.

The WRLU dataset was primarily selected to assist in distinguishing fallow and dry land agriculture from impervious surfaces. Three agricultural land use classes – irrigated, sub-irrigated, and non-irrigated – were selected from the WRLU data and merged to create an agriculture dataset. Additionally, other classes within the WRLU data, including water, riparian, and urban parks, were extracted from the dataset. These classes were considered valuable for classifying water, riparian and wetland areas, and urban parks, respectively (Figure 4-13).

The road centerline dataset (Figure 4-14) was selected as an ancillary dataset that would assist in accounting for roads occurring within spectrally similar areas, such as those occurring within a fallow agricultural field. Within the attribute table of the road centerline data, there is a field with the heading of CARTOCODE. This attribute represents the cartographic code and defines each road centerline segment by road type (Table 4-2). The maximum road width for each road type was defined by using established road widths (Xiong, 2000) (Table 4-3). The maximum road widths for each road type were either verified or adjusted to best represent the road widths within the three sub-basins. The attribute table was updated with two new columns depicting maximum road width and buffer width. The buffer width was used to buffer the road centerline segments.

The stream dataset was selected to be used in conjunction with the water class from the WRLU data because the WRLU data have limitations in terms of extent (Figure 4-15). Since the stream dataset represents the entire surface water drainage system, extraneous data, including ephemeral and intermittent streams, dry washes, and buried canals, were removed from the dataset. The remaining river, stream, and canal segments were buffered by 10 meters. The soils data were used to assist in differentiating playa and alkaline soils adjacent to the Great Salt Lake from impervious surfaces. Soils adjacent to the Great Salt Lake with high brightness values, such as Saltair Silty Clay Loam, Jordan Silty Clay Loam, Lasil Silt Loam, Magna Silty Clay, and Terminal Silt Loam, were extracted from the data (Figure 4-16).

The 1/3 arc-second (approximately 10 meter) NED data were used to identify elevational breaks of change within each sub-basin. Elevational breaks were defined in Esri ArcGIS and three polygons were created (Figure 4-17). Elevation data in the form of a raster can be directly used in eCognition. However, when imported as a raster file, the mean statistics for image bands and several object features are affected. Therefore, vector data were preferably used. For the Jordan sub-basin, three polygons were generated to define elevations below 1,283 meters (4,209 feet), elevations between 1,750 (5,741 feet) and 2,700 meters (8,858 feet), and elevations above 2,700 meters (8,858 feet). These three breaks were selected to support the classification of general vegetation and land cover types within these areas. For instance, areas above 1,750 meters (5,741 feet) in the Jordan sub-basin are typically characterized by forested, alpine, and subalpine land cover types and have few urban and suburban areas.

After the data were extracted and processed in Esri ArcGIS, the ancillary datasets were imported into eCognition as thematic layers using the chessboard segmentation algorithm. The chessboard segmentation algorithm is a top-down segmentation process that divides, or tiles, data sets into equal and square image objects based on a specified size. This algorithm is useful for incorporating vector data into an eCognition project because it converts thematic data into image objects (Trimble, 2014).

Following the import process in eCognition, the thematic layers were used as analysis masks to improve class differentiation and model results. Within the bounds of each thematic layer, multiresolution and spectral difference segmentation algorithms were applied, and rules were developed and customized to classify segments. For instance, the water class from the WRLU data was used to refine the extent and improve the accuracy of water features. Although the WRLU data are detailed enough for state- and county-wide use, the data are digitized from digital orthophotos. Depending on the scale at which the data were digitized, boundaries may be simplified and intersecting land uses may be concealed. By integrating the extents of WRLU data into the eCognition rule set development process, more accurate representations can be achieved (Figure 4-18).

The segments within the thematic layers were assigned to one of the nine classes and the remaining unclassified segments were classified using a variety of spectral-, spatial-, and context-based rules (Figure 4-19). To determine the most appropriate threshold values for each rule within the entire rule set, values were iteratively adjusted and rules were executed using several small image subsets within the Jordan sub-basin. A series of adjustments were made to identify average optimal threshold values because optimal threshold values for one image subset were frequently different from those for another image subset. These variations are generally attributed to differences in imagery collection dates, whereby atmospheric conditions may be dissimilar.

The process of rule set development for the Jordan watershed sub-basin served as the foundation for the methodology of this project. Once an approach for developing high-resolution LULC information using eCognition was established and outlined, the process of developing rule sets for the Lower Weber and Lower Bear-Malad sub-basins was relatively straightforward. For both sub-basins, ancillary data sets were extracted and prepared in Esri ArcGIS, data were imported into eCognition, and rules were iteratively developed and evaluated.

Image Classification

Following rule set development, a dedicated workspace for each of the three sub-basins was created. A workspace is a directory that contains and stores projects, raster and vector data, rule sets, and classification results. Workspaces are an efficient and necessary requirement of processing large data sets and for using the batch processing function in eCognition Server. eCognition Server is a software component which is typically run on a dedicated server. It can analyze large images and quantities of data by applying automatic tiling and stitching methods. Using the batch processing function in eCognition Server, each sub-basin was tiled into image subsets with the spatial dimensions of 3,000 pixels by 3,000 pixels. The finalized rule set was uploaded and the processing of tiles was initiated.

After each sub-basin was processed in eCognition Server, the workspaces containing the classification results were copied to individual workstations for manual editing. Manual editing in eCognition is an optional step; however, the accuracy of results can be increased. Tiles were reviewed in eCognition Developer and necessary edits were performed to increase accuracy. Some of the misclassification errors that were identified during the editing process included barren lands classified as impervious surfaces, riparian/wetland areas classified as agriculture, and vegetation classified as sparse vegetation. Some of these errors were attributed to the use of the WRLU data (i.e. riparian/wetland areas were occasionally classified as agriculture). It was also noted during the manual editing phase that certain areas with the sub-basins had higher accuracies than other areas. As with identifying optimal threshold values for rules, these variations may be attributed to differences in imagery collection dates and atmospheric conditions.

The edited tiles were stitched together in eCognition Server, and subsequently reviewed in entirety for seamline inconsistencies and additional misclassification errors. The final results were exported as file geodatabases and opened in Esri ArcGIS. Although file geodatabases do not have file size limitations, there are feature class and table limitations. The output files did not exceed these limits, but they did have a significant number of feature classes, approaching 20 million polygons. Drawing time was slow, and processing of the complete dataset was not feasible. Therefore, the image classification for each sub-basin was parsed into subsets using USGS quadrangle boundaries. The USGS subsets provided for more efficient and improved data management. Using the subsets, the LULC classes were numerically coded for raster conversion. The subsets was converted to raster datasets and were mosaicked to create seamless sub-basin composites (Figures 4-20 through 4-24).

Results

Accuracy Assessment

Accuracy assessments of the LULC classification results were conducted for the three sub-basins. Accuracy assessments provide a means of assessing the quality of the results and are needed to identify and understand the nature of errors. Accuracy assessments generally involve the comparison of results with independently collected verification data. Verification, or ground truth, data may be acquired from field samples or may be interpreted from imagery (Aronoff, 2005). For this analysis, an accuracy assessment was conducted using randomly generated point data. Points were randomly generated in Esri ArcGIS, with a higher density of points being placed within urban areas. Point data were populated with verification data by manual interpreting LULC classes from the 2011 NAIP aerial imagery.

The point data were sampled through the LULC classification results using the *Extract Values to Points* tool in Esri ArcGIS. Using the *Frequency* and *Pivot Table* tools, error matrices and classification accuracies were generated (Tables 4-4 through 4-6). Error matrices, also known as contingency tables or confusion matrices, provide a basis on which to describe classification accuracy and to characterize classification errors (Jensen, 2005). Important measures, such as the overall accuracy, producer's accuracy, user's accuracy, and kappa coefficient of agreement, can be calculated from error matrices.

The overall accuracy is determined by the dividing the total number of correctly classified points (i.e. sum of the major diagonal) by the total number of points. The accuracies of individual classes were also calculated; however, computing the accuracy of individual classes is more complex. Traditionally, the total number of correctly classified verification, or ground truth, points within a class is divided by the total number of verification points for the specified class (i.e. column total). This statistic indicates the probability of a verification point being correctly classified and is a measure of omission error. This statistic is called the producer's accuracy because the producer (the analyst) of the classification is interested in how well a certain area can be classified. If the total number of verification points for a specified class is divided by the total number of verification points that were actually classified in that class (i.e. row total), the result is a measure of commission error. This measure, called the user's accuracy or reliability, is the probability that a point classified on the map actually represents that class on the ground. The kappa coefficient of agreement is a measure of agreement between the remote-sensing derived classification and the verification data as indicated by the major diagonal and the chance of agreement, which is indicated by the row and column totals (Jensen, 2005).

The overall accuracies of the LULC classifications for Lower Bear-Malad, Lower Weber, and Jordan sub-basins are 98.81, 97.15, and 98.37 percent, respectively. While the overall quantitative accuracies indicate that the classification results are exceptional, there are some qualitative errors worth mentioning. Incorporation of ancillary data sets and manual editing considerably improved classification results. However, as a result of using the WRLU data, the errors inherent to the dataset were propagated into the classification results. For example, some urban parks or riparian/wetland areas were not classified in the WRLU data;

therefore, these features ended up being classified as vegetation. Additionally, riparian/wetland areas were occasionally classified as agriculture in the WRLU dataset; therefore, these areas ended up being classified as agriculture. Some of these errors were corrected during the manual editing process, but due to size of the study area and the spatial resolution of the LULC information, not all misclassification errors could be corrected. Lastly, the qualitative evaluation of the results suggest that mixed pixels are present. For example, the borders of rooftops were occasionally classified as sparse vegetation. This classification error is predominantly the result of pixels being composed of both impervious and vegetated land cover types. However, due to the high spatial resolution of the imagery and data, this issue is not significant.

Watershed-Scale Quantifications

Quantifications of impervious surface and the eight other LULC classes were generated for the three sub-basins (HUC 8) and for the watersheds (HUC 10) occurring within the three sub-basins. There are 14 watersheds within the three sub-basins. Three watersheds are located within the Lower Bear-Malad sub-basin: Bear River-Frontal Great Salt Lake, Malad River-Bear River, and Whites Valley. Seven watersheds are located within the Lower Weber sub-basin: Cottonwood Creek-Weber River, East Canyon Creek, Farmington Creek-Frontal Farmington Bay, Headwaters Ogden River, Outlet Ogden River, Third Salt Creek-Frontal Great Salt Lake, and Weber River-Frontal Great Salt Lake. Four watersheds are located within Jordan sub-basin: Big Cottonwood Creek-Jordan River, Bingham Creek-Jordan River, Jordan River-Frontal Great Salt Lake, and Mill Creek-Jordan River (Figure 4-25).

Total land area calculations for the three sub-basins and the 14 watersheds were generated (Table 4-7). For the three sub-basins and 14 watersheds, quantifications of the LULC classes were generated (Tables 4-8 through 4-10). These quantifications were summarized by sub-basin (Table 4-11), and the total area of impervious surface and percent imperviousness for the 14 watersheds were summarized by watershed (Table 4-12).

Conclusion and Implications

A high-resolution LULC dataset, with a primary emphasis on mapping and quantifying impervious surfaces, was developed for three sub-basins – Lower Bear-Malad, Lower Weber, and Jordan – spanning the northern two-thirds of the highly urbanized Wasatch Front. This dataset was identified as a means to support integrated water resources planning and management in northern Utah, namely to support Utah's WPP and Utah's Watershed Approach to managing nonpoint source pollution. This classificatioin was generated by applying OBIA methods to the 2011 four-band NAIP aerial imagery. Ancillary data sets, including WRLU data, road centerline data, stream data, soils data, and NED data, were incorporated into the rule set development process to improve classification results. The overall accuracies for Lower Bear-Malad, Lower Weber, and Jordan sub-basins are 98.81, 97.15, and 98.37 percent, respectively. The combined accuracy of the three sub-basin classifications is 97.85 percent.

Impervious surface land cover datasets have become increasingly important and prevalent for addressing the impacts of urban development on water resources and aquatic ecosystems. The amount of impervious surface area within a watershed has been identified as a key indicator and predictor of watershed health (Arentsen et al., 2004; Zhou and Weng, 2006). Impervious surface land cover datasets are valuable in that they are integrative, measurable, and cost-effective. They can be used to estimate or predict cumulative water resource impacts without regard to specific factors; they can be quantified for use in planning and regulatory applications; and they are an economical approach for addressing water pollution in locations where there is limited hydrologic information (Arnold and Gibbons, 1996; Schueler et al., 2009). In terms of integrated planning efforts in Utah, an impervious surface land cover dataset can (1) serve as an indicator of cumulative stress from urbanization, (2) support the development of ecologically relevant and scientifically defensible metrics that can be integrated into wetland condition assessments, (3) provide general assessments of watershed and wetland condition within or near urban areas, (4) support the identification of thresholds of imperviousness that could predict watershed impairment, and (5) support the identification of sites in need of restoration or protection.

In the absence of hydrologic models or information, an impervious surface land cover dataset can be used in conjunction with the original and reformulated ICM (Schueler, 1994; Schueler et al., 2009) to provide general estimates of watershed condition. Although the ICM threshold values and ranges may be debatable, they can provide watershed planners, water quality scientists, and policy makers with a reasonable foundation for outlining and supporting water quality objectives, stormwater practices, land use controls, and monitoring and restoration efforts (Schueler, 1994; Schueler et al., 2009).

Using the original ICM threshold values, the impervious surface quantifications at the watershed (HUC 10) level suggest that the eight of the watersheds are classified as sensitive (1-10 percent impervious cover); six of the watersheds are classified as impacted (10-25 percent impervious cover); and none of the watersheds are classified as non-supporting (25-60 percent impervious cover) or urban (60-100 percent impervious cover). However, based on the reformulated ICM, one watershed (i.e. Cottonwood Creek-Weber River) is in the transition phase from sensitive to impacted (5-10 percent impervious cover), and one watershed (i.e. Mill Creek-Jordan River) is in the transition from impacted to non-supporting (20-25 percent impervious cover) (Figure 4-26; Table 4-13).

Although these ICM watershed condition estimates provide meaningful information at broad scales, they may not be entirely representative of actual conditions. Due to certain variables, such as the size and extent of watersheds, land ownership, urbanization patterns, and topography in northern Utah, ICM estimates at the watershed (HUC 10) scale may conceal or overstate watershed conditions. For instance, some of the upper reaches of watersheds may be predominantly comprised of forested lands, but the lower reaches are comprised of urban land cover types. This composition may preclude the evaluation of watersheds that are actually at risk or may suggest that upper reaches are at risk when their hydrological integrity is predominantly intact. To provide a more complete representation, an evaluation was warranted using sub-watershed (HUC 12) boundaries. Within the study area, there are 78 sub-watersheds, with 16 occurring in Lower Bear-Malad, 37 occurring with Lower Weber, and 25 occurring within

Jordan. This evaluation suggested that 48 sub-watersheds are sensitive; seven sub-watersheds are in the transition phase from sensitive to impacted; 10 sub-watersheds are impacted; five sub-watersheds are in the transition phase from impacted to non-supporting; and eight sub-watersheds are non-supporting. The Jordan sub-basin encompasses seven of the eight sub-watersheds that are classified as non-supporting (25-60 percent impervious cover) (Figure 4-27).

This information can be paired with water quality assessments, if available, to validate results and to identify and prioritize restoration sites. In the state of Utah, the UDWQ is required to generate a list of impaired waters, as mandated under the Clean Water Act. As an element of this requirement, the UDWQ has created a spatial dataset that characterizes the designated uses (i.e. the level of impairment) of waterbodies in Utah. These designated uses are based on a five-category system developed by the EPA. Category 1 suggests that all designated uses are attained and that water quality is not impaired. Category 2 suggests that some of the designated uses are attained, but there may be insufficient data to determine if the remaining designated uses are supported. Category 3 suggests that there are insufficient data to make a determination of water quality. Category 4 suggests that the water is impaired for one or more designated uses, but the level of impairment has not yet required the development of regulations. Category 5 suggests that the designated uses are not supported (i.e. the water is impaired and requires regulation) because several pollutants exceed numeric water quality criteria (UDWQ, 2014). The spatial data associated with these water quality assessments are fairly consistent with the HUC 12 ICM assessments (Figure 4-28). Although the assessment units defined by the UDWQ do not exactly correspond with the HUC 12 units, there is a strong parallel between impaired assessment units and impaired watershed sub-basins. The congruence between the two assessments confirms that an impervious surface dataset can indeed serve as a feasible and cost-effective approach for addressing water pollution, especially in locations where there may be limited information on pollutant loadings, hydrologic modeling, and management practices.

Lastly, in addition to using the ICM to provide general assessments of watershed or sub-watershed conditions, an impervious surface land cover dataset can be used by county and city planners and administrators, stormwater engineers, and water quality scientists to generate detailed information at a parcel level. Parcel-based impervious surface information (i.e. percent impervious surface) can promote an improved understanding of urban hydrological systems; can assist in modelling drainage connectivity; can support the identification of sources and locations of concentrated urban runoff; and can contribute to precipitation retention and infiltration calculations (Stone, 2004; Buchan, 2006; Verbeeck et al., 2014). Parcel-based LULC information can be used to develop county- and municipal-based land use policies, zoning regulations, and management practices that encourage low impact development and/or more sustainable urban drainage systems. For instance, jurisdictions can apply stormwater taxes or surcharges based on thresholds of impervious cover (Hodgson et al., 2003; Kienegger, 1992). For demonstration and implication purposes, an example of this type of information was developed using the LULC information for the Jordan sub-basin and Salt Lake County parcel data (Figures 4-29 and 4-30).

Regardless of the assessment method (i.e. ICM estimates or parcel-based inventories of impervious cover), more thorough evaluations of watershed condition can be achieved by integrating other metrics and data, if available. Land cover metrics, such as amount, composition, and connectivity of land cover types, should be incorporated into models. In this instance, the high-resolution LULC information developed for this analysis could support this effort. Land cover runoff coefficients, which relate to the amount of runoff relative to the amount of precipitation received, can provide valuable inputs regarding hydrologic responses and nonpoint source pollution. Runoff coefficients are higher for areas with low infiltration and/or steep gradients (e.g. impervious surfaces) and are lower for areas with highly vegetated surfaces and/or shallow gradients (e.g. forested meadows) (Sriwongsitanon and Taesombat, 2011; CEPA, 2011). Average watershed slope, which could be derived from a digital elevation model, can provide a general indication of slope stability and potential for runoff (Cooper, 2011). Agricultural, forest harvesting, and range practices should be included into models to account for potential contributions to water quality degradation. Lastly, road density should be incorporated into models because roads can be significant sources of nonpoint source pollution and can increase the delivery of sediments, heavy metals, hydrocarbons, and other pollutants into waterways (Schueler, 1994; Copper, 2011).

High-resolution LULC information at the sub-basin scale, when combined with other metrics that influence water quality, can be used to conduct fairly detailed watershed condition and water quality risk assessments. These assessments, which can be translated into policy-relevant information, have become essential elements of integrated planning, management, and decision-making activities. These assessments can also serve as indispensable tools for identifying and prioritizing water quality improvement projects.

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Tables

Table 4-1. LULC classes for the three sub-basins.

LULC CLASSES		
CODE	CLASS	DESCRIPTION
1	Agriculture	Planted/cultivated fields; fallow fields
2	Barren/Bedrock	Playa; gravel pits, rocky outcrops, dirt roads, parcels slated for development
3	Impervious Surfaces	Urban infrastructure (i.e. paved roads, parking lots, sidewalks, buildings)
4	Riparian/Wetland	Riverine/riparian vegetation; marshes/wetlands
5	Snow	Snow
6	Sparse Vegetation	Semi-desert shrubland; senesced vegetation; herbaceous/invasive grasses/forbs
7	Urban Parks	Parks/fields; golf courses; cemeteries
8	Vegetation	Forest; woodland; urban tree canopy; turf/grass
9	Water	Rivers/streams/canals; lakes/reservoirs; treatment facilities

Table 4-2. Cartographic code attribute definitions for the road centerline data.

UTAH AGRC CARTOGRAPHIC CODE (CARTOCODE)	
CODE	TYPE OF ROAD
1	Interstates
2	US Highway, Separated
3	US Highway, Unseparated
4	Major State Highway, Separated
5	Major State Highway, Unseparated
6	Other State Highway (Institutional)
7	Ramps, Collectors
8	Major Local Roads, Paved
9	Major Local Roads, Not Paved
10	Other Federal Aid Eligible Local Roads
11	Other Local, Neighborhood, Rural Roads
12	Other (i.e. Roads within ski resorts)

Table 4-3. Average widths of roads by functional class (Xiong, 2000).

AVERAGE WIDTHS OF ROADS							
HIGHWAY FUNCTIONAL CLASS	CLASS CODE	PAVEMENT		MEDIAN		RIGHT-OF-WAY	
Rural Principal Arterial – Interstate	1	23.5 m	77.2 ft	19.6 m	64.4 ft	57.9 m	189.9 ft
Rural Principal Arterial – Other	2	13.4 m	44.0 ft	3.1 m	10.3 ft	30.7 m	100.6 ft
Rural Minor Arterial	6	10.6 m	34.7 ft	0.5 m	1.7 ft	21.9 m	71.9 ft
Rural Major Collector	7	10.9 m	35.6 ft	0 m	0 ft	21.9 m	71.8 ft
Rural Minor Collector	8	8.5 m	28.0 ft	0 m	0 ft	26.5 m	86.9 ft
Rural Local	9	20.3 m	66.5 ft	11.6 m	37.9 ft	63.6 m	208.5 ft
Urban Principal Arterial – Interstate	11	17.3 m	56.6 ft	9.5 m	31.2 ft	52.0 m	170.7 ft
Urban Principal Arterial – Other Freeways and Expressways	12	11.3 m	37.0 ft	3.2 m	10.4 ft	22.1 m	72.6 ft
Urban Principal Arterial – Other	14	11.6 m	38.2 ft	2.8 m	9.3 ft	19.1 m	62.6 ft
Urban Minor Arterial	16	8.6 m	28.1 ft	0.2 m	0.8 ft	11.4 m	37.4 ft
Urban Collector	17	8.4 m	27.4 ft	0 m	0 ft	14.8 m	48.5 ft
Urban Local	19	9.9 m	32.5 ft	1.4 m	4.6 ft	20.2 m	66.4 ft

Table 4-4. Error matrix for Lower Bear-Malad sub-basin LULC classification.

	CLASS	VERIFICATION/GROUND TRUTH DATA (ACTUAL)									
		Agriculture	Barren/Bedrock	Impervious	Riparian/Wetland	Sparse Vegetation	Urban Parks	Vegetation	Water	**Row Total**	**User´s Accuracy**
REMOTE SENSING CLASSIFICATION (PREDICTED)	Agriculture	340	0	0	0	2	0	0	0	342	99.4%
	Barren/Bedrock	0	194	6	0	1	0	0	0	201	96.5%
	Impervious	0	0	614	0	0	0	0	0	614	100.0%
	Riparian/Wetland	0	0	0	193	1	0	0	1	195	99.0%
	Sparse Vegetation	0	0	2	2	310	0	2	0	316	98.1%
	Urban Parks	0	0	0	0	0	10	0	0	10	100.0%
	Vegetation	0	1	1	2	1	0	286	0	291	98.3%
	Water	0	0	0	3	0	0	0	128	131	97.7%
	Column Total	340	195	623	200	315	10	288	129	2100	
	Producer´s Accuracy	100.0%	99.5%	98.6%	96.5%	98.4%	100.0%	99.3%	99.2%		
	Overall Accuracy	98.81%									
	Kappa Coefficient of Agreement (Unweighted)	0.9855									

Table 4-5. Error matrix for Lower Weber sub-basin LULC classification.

	CLASS	Agriculture	Barren/Bedrock	Impervious	Riparian/Wetland	Snow	Sparse Vegetation	Urban Parks	Vegetation	Water	Row Total	User´s Accuracy
		VERIFICATION/GROUND TRUTH DATA (ACTUAL)										
REMOTE SENSING CLASSIFICATION (PREDICTED)	Agriculture	535	1	0	4	0	20	0	5	0	565	94.7%
	Barren/Bedrock	3	341	7	1	1	28	0	0	1	382	89.3%
	Impervious	0	3	2728	0	0	0	0	0	1	2732	99.9%
	Riparian/Wetland	1	3	0	295	0	2	0	3	0	304	97.0%
	Snow	0	0	0	0	22	0	0	0	0	22	100.0%
	Sparse Vegetation	5	19	13	2	0	617	0	26	1	683	90.3%
	Urban Parks	0	0	0	0	0	0	106	0	0	106	100.0%
	Vegetation	2	0	3	22	0	4	5	1668	0	1704	97.9%
	Water	0	1	0	4	0	0	0	0	197	202	97.5%
	Column Total	546	368	2751	328	23	671	111	1702	200	6700	
	Producer´s Accuracy	98.0%	92.7%	99.2%	89.9%	95.7%	92.0%	95.5%	98.0%	98.5%		
	Overall Accuracy	97.15%										
	Kappa Coefficient of Agreement (Unweighted)	0.9617										

Table 4-6. Error matrix for Jordan sub-basin LULC classification.

	CLASS	VERIFICATION/GROUND TRUTH DATA (ACTUAL)										
		Agriculture	Barren/Bedrock	Impervious	Riparian/Wetland	Snow	Sparse Vegetation	Urban Parks	Vegetation	Water	Row Total	User´s Accuracy
REMOTE SENSING CLASSIFICATION (PREDICTED)	Agriculture	208	0	0	0	0	25	2	1	0	236	88.1%
	Barren/Bedrock	0	368	2	0	0	2	0	0	0	372	98.9%
	Impervious	2	17	2639	0	0	1	0	1	0	2660	99.2%
	Riparian/Wetland	0	0	0	136	0	0	0	2	0	138	98.6%
	Snow	0	0	0	0	31	0	0	0	0	31	100.0%
	Sparse Vegetation	1	5	3	0	0	444	0	4	0	457	97.2%
	Urban Parks	0	0	0	0	0	2	189	2	0	193	97.9%
	Vegetation	0	0	2	1	0	2	4	999	0	1008	99.1%
	Water	0	0	1	3	0	0	0	0	101	105	96.2%
	Column Total	211	390	2647	140	31	476	195	1009	101	5200	
	Producer´s Accuracy	98.6%	94.4%	99.7%	97.1%	100.0%	93.3%	96.9%	99.0%	100.0%		
	Overall Accuracy	98.37%										
	Kappa Coefficient of Agreement (Unweighted)	0.9827										

Table 4-7. Total land area in square kilometers (and square miles) for sub-basins and watersheds.

SUB-BASIN (HUC 8)	WATERSHED (HUC 10)
Lower Bear-Malad (16010204) 1,934.43 sq km (746.89 sq miles)	Bear River-Frontal Great Salt Lake (1601020405) 911.38 sq km (351.89 sq miles)
	Malad River-Bear River (1601020403) 681.12 sq km (262.98 sq miles)
	Whites Valley (1601020404) 341.93 sq km (132.02 sq miles)
Lower Weber (16020102) 3,419.58 sq km (1320.31 sq miles)	Cottonwood Creek-Weber River (1602010204) 701.62 sq km (270.90 sq miles)
	East Canyon Creek (1602010201) 615.79 sq km (237.76 sq miles)
	Farmington Creek-Frontal Farmington Bay (1602010205) 587.53 sq km (226.85 sq miles)
	Headwaters Ogden River (1602010202) 371.39 sq km (143.40 sq miles)
	Outlet Ogden River (1602010203) 491.61 sq km (189.81 sq miles)
	Third Salt Creek-Frontal Great Salt Lake (1602010207) 315.31 sq km (121.74 sq miles)
	Weber River-Frontal Great Salt Lake (1602010206) 336.32 sq km (129.86 sq miles)
Jordan (16020204) 2,106.43 sq km (813.30 sq miles)	Big Cottonwood Creek-Jordan River (1602020402) 457.72 sq km (176.72 sq miles)
	Bingham Creek-Jordan River (1602020401) 514.30 sq km (198.57 sq miles)
	Jordan River-Frontal Great Salt Lake (1602020404) 615.82 sq km (237.77 sq miles)
	Mill Creek-Jordan River (1602020403) 518.59 sq km (200.23 sq miles)

Table 4-8. LULC area calculations in hectares and acres for Lower Bear-Malad sub-basin and watersheds comprising Lower Bear-Malad sub-basin.

SUB-BASIN (HUC 8)

Lower Bear-Malad (16010204)

	Area (Hectares)	Area (Acres)
Total Area:	**193,443.00**	**478,007.34**
Agriculture:	46,625.12	115,213.00
Barren/Bedrock:	21,266.07	52,549.52
Impervious:	2,803.93	6,928.65
Riparian/Wetland:	17,247.96	42,620.57
Snow:	0.06	0.15
Sparse Vegetation:	64,084.47	158,355.93
Urban Parks:	238.58	589.55
Vegetation:	25,168.65	62,192.99
Water:	16,008.16	39,556.96

WATERSHED (HUC 10)

Bear River-Frontal Great Salt Lake (1601020405)

	Area (Hectares)	Area (Acres)
Total Area:	**91,138.33**	**225,207.36**
Agriculture:	11,550.56	28,542.00
Barren/Bedrock:	18,382.32	45,423.63
Impervious:	1,439.15	3,556.22
Riparian/Wetland:	14,075.87	34,782.17
Snow:	0.06	0.15
Sparse Vegetation:	20,170.08	49,841.28
Urban Parks:	136.27	336.73
Vegetation:	10,126.11	25,022.12
Water:	15,257.91	37,703.07

Malad River-Bear River (1601020403)

	Area (Hectares)	Area (Acres)
Total Area:	**68,111.81**	**168,307.69**
Agriculture:	23,761.49	58,715.83
Barren/Bedrock:	1,658.62	4,098.53
Impervious:	860.47	2,126.28
Riparian/Wetland:	1,869.48	4,619.58
Sparse Vegetation:	25,968.41	64,169.23
Urban Parks:	65.32	161.40
Vegetation:	13,408.08	33,132.04
Water:	519.95	1,284.81

Whites Valley (1601020404)

	Area (Hectares)	Area (Acres)
Total Area:	**34,192.86**	**84492.28**
Agriculture:	11,313.07	27,955.17
Barren/Bedrock:	1,225.13	3,027.36
Impervious:	504.30	1,246.16
Riparian/Wetland:	1,302.61	3,218.83
Sparse Vegetation:	17,945.99	44,345.43
Urban Parks:	37.00	91.43
Vegetation:	1,634.46	4,038.83
Water:	230.30	569.08

Table 4-9. LULC area calculations in hectares and acres for Lower Weber sub-basin and watersheds comprising Lower Weber sub-basin (continued on next page).

SUB-BASIN (HUC 8)			WATERSHED (HUC 10)		
Lower Weber (16020102)			**Cottonwood Creek-Weber River (1602010204)**		
	Area (Hectares)	Area (Acres)		Area (Hectares)	Area (Acres)
Total Area:	**341,957.59**	**844,994.31**	**Total Area:**	**70,161.52**	**173,372.62**
Agriculture:	30,555.34	75,503.77	Agriculture:	3,809.97	9,414.63
Barren/Bedrock:	22,492.17	55,579.28	Barren/Bedrock:	3,431.94	8,480.49
Impervious:	20,887.21	51,613.33	Impervious:	3,645.82	9,009.00
Riparian/Wetland:	15,345.94	37,920.59	Riparian/Wetland:	534.02	1,319.58
Snow:	26.39	65.20	Snow:	15.69	38.77
Sparse Vegetation:	87,259.42	215,622.39	Sparse Vegetation:	22,947.89	56,705.38
Urban Parks:	1,946.19	4,809.14	Urban Parks:	369.69	913.51
Vegetation:	149,826.26	370,228.19	Vegetation:	35,191.37	86,959.63
Water:	13,618.67	33,652.41	Water:	215.14	531.61
			East Canyon Creek (1602010201)		
				Area (Hectares)	Area (Acres)
			Total Area:	**61,579.05**	**152,164.90**
			Agriculture:	2,654.49	6,559.37
			Barren/Bedrock:	979.65	2,420.77
			Impervious:	1,250.28	3,089.50
			Riparian/Wetland:	944.90	2,334.88
			Snow:	4.04	9.98
			Sparse Vegetation:	17,867.10	44,150.49
			Urban Parks:	183.95	454.54
			Vegetation:	37,346.45	92,284.94
			Water:	348.20	860.41
			Farmington Creek-Frontal Farmington Bay (1602010205)		
				Area (Hectares)	Area (Acres)
			Total Area:	**58,753.38**	**145,182.54**
			Agriculture:	6,953.18	17,181.66
			Barren/Bedrock:	3,286.03	8,119.95
			Impervious:	9,677.34	23,913.18
			Riparian/Wetland:	7,355.57	18,175.98
			Snow:	2.39	5.92
			Sparse Vegetation:	7,795.43	19,262.90
			Urban Parks:	853.99	2,110.26
			Vegetation:	21,955.35	54,252.76
			Water:	874.09	2,159.93
			Headwaters Ogden River (1602010202)		
				Area (Hectares)	Area (Acres)
			Total Area:	**37,139.24**	**91,772.93**
			Agriculture:	179.64	443.90
			Barren/Bedrock:	1,795.11	4,435.81
			Impervious:	80.62	199.22
			Riparian/Wetland:	164.04	405.34
			Sparse Vegetation:	11,499.12	28,414.90
			Vegetation:	23,319.10	57,622.66
			Water:	101.61	251.09

Table 4-9 (continued). LULC area calculations in hectares and acres for Lower Weber sub-basin and watersheds comprising Lower Weber sub-basin.

SUB-BASIN (HUC 8)			WATERSHED (HUC 10)		
Lower Weber (16020102)			Outlet Ogden River (1602010203)		
	Area (Hectares)	Area (Acres)		Area (Hectares)	Area (Acres)
Total Area:	**341,957.59**	**844,994.31**	**Total Area:**	**49,160.79**	**121,478.76**
Agriculture:	30,555.34	75,503.77	Agriculture:	3,893.51	9,621.07
Barren/Bedrock:	22,492.17	55,579.28	Barren/Bedrock:	2,705.99	6,686.65
Impervious:	20,887.21	51,613.33	Impervious:	971.88	2,401.57
Riparian/Wetland:	15,345.94	37,920.59	Riparian/Wetland:	452.94	1,119.24
Snow:	26.39	65.20	Snow:	3.91	9.67
Sparse Vegetation:	87,259.42	215,622.39	Sparse Vegetation:	15,389.74	38,028.82
Urban Parks:	1,946.19	4,809.14	Urban Parks:	131.66	325.34
Vegetation:	149,826.26	370,228.19	Vegetation:	24,442.97	60,399.79
Water:	13,618.67	33,652.41	Water:	1,168.17	2,886.61
			Third Salt Creek-Frontal Great Salt Lake (1602010207)		
				Area (Hectares)	Area (Acres)
			Total Area:	**31,531.25**	**779,15.30**
			Agriculture:	4,906.46	12,124.10
			Barren/Bedrock:	7,032.51	17,377.67
			Impervious:	629.67	1,555.94
			Riparian/Wetland:	2,234.18	5,520.77
			Snow:	0.33	0.81
			Sparse Vegetation:	5,502.62	13,597.24
			Urban Parks:	61.85	152.83
			Vegetation:	1,653.98	4,087.07
			Water:	9,509.67	23,498.86
			Weber River-Frontal Great Salt Lake (1602010206)		
				Area (Hectares)	Area (Acres)
			Total Area:	**33,632.37**	**83,107.27**
			Agriculture:	8,158.08	20,159.04
			Barren/Bedrock:	3,260.94	8,057.94
			Impervious:	4,631.60	11,444.91
			Riparian/Wetland:	3,660.30	9,044.80
			Snow:	0.02	0.06
			Sparse Vegetation:	6,257.52	15,462.65
			Urban Parks:	345.06	852.65
			Vegetation:	5,917.05	14,621.34
			Water:	1,401.79	3,463.89

Table 4-10. LULC area calculations in hectares and acres for Jordan sub-basin and watersheds comprising Jordan sub-basin.

SUB-BASIN (HUC 8)

Jordan (16020204)	Area (Hectares)	Area (Acres)
Total Area:	**210,642.65**	**520,508.52**
Agriculture:	12,344.32	30,503.43
Barren/Bedrock:	23,500.77	58,071.57
Impervious:	36,589.96	90,415.63
Riparian/Wetland:	6,857.49	16,945.19
Snow:	502.91	1,242.72
Sparse Vegetation:	46,856.11	115,783.79
Urban Parks:	3,250.68	8,032.60
Vegetation:	76,366.71	188,705.97
Water:	4,373.69	10,807.62

WATERSHED (HUC 10)

Big Cottonwood Creek-Jordan River (1602020402)	Area (Hectares)	Area (Acres)
Total Area:	**45,771.52**	**113,103.71**
Agriculture:	1,869.96	4,620.75
Barren/Bedrock:	4,301.55	10,629.35
Impervious:	8,029.54	19,841.39
Riparian/Wetland:	214.67	530.46
Snow:	406.30	1,003.99
Sparse Vegetation:	8,147.46	20,132.78
Urban Parks:	647.11	1,599.04
Vegetation:	21,993.57	54,347.20
Water:	161.37	398.75

Bingham Creek-Jordan River (1602020401)	Area (Hectares)	Area (Acres)
Total Area:	**51,429.98**	**127,086.06**
Agriculture:	5,529.30	13,663.17
Barren/Bedrock:	6,254.28	15,454.63
Impervious:	10,191.12	25,182.76
Riparian/Wetland:	541.92	1,339.11
Snow:	94.24	232.88
Sparse Vegetation:	13,049.63	32,246.29
Urban Parks:	960.98	2,374.64
Vegetation:	14,570.75	36,005.06
Water:	237.76	587.51

Jordan River-Frontal Great Salt Lake (1602020404)	Area (Hectares)	Area (Acres)
Total Area:	**61,582.10**	**152,172.44**
Agriculture:	4,590.44	11,343.20
Barren/Bedrock:	12,018.54	29,698.41
Impervious:	7,936.64	19,611.83
Riparian/Wetland:	5,923.40	14,637.02
Snow:	0.30	0.73
Sparse Vegetation:	18,375.58	45,406.98
Urban Parks:	559.31	1,382.07
Vegetation:	8,473.63	20,938.76
Water:	3,704.26	9,153.42

Mill Creek-Jordan River (1602020403)	Area (Hectares)	Area (Acres)
Total Area:	**51,859.05**	**128,146.31**
Agriculture:	354.63	876.31
Barren/Bedrock:	926.40	2,289.17
Impervious:	10,432.67	25,779.65
Riparian/Wetland:	177.49	438.60
Snow:	2.07	5.12
Sparse Vegetation:	7,283.44	17,997.74
Urban Parks:	1,083.28	2,676.84
Vegetation:	31,328.77	77,414.95
Water:	270.30	667.93

Table 4-11. Total area of LULC and percent LULC for the three sub-basin. Calculations of impervious surface are highlighted.

SUB-BASIN (HUC 8)	LAND COVER CLASS	TOTAL AREA (Hectares)	TOTAL AREA (Acres)	PERCENT LAND COVER
	Agriculture	46,625.12	115,213.00	24.10%
Lower Bear-Malad	Barren/Bedrock	21,266.07	52,549.52	10.99%
(16010204)	**Impervious**	**2,803.93**	**6,928.65**	**1.45%**
	Riparian/Wetland	17,247.96	42,620.57	8.92%
Area:	Snow	0.06	0.15	0.00%
193,443.00 Hectares	Sparse Vegetation	64,084.47	158,355.94	33.13%
478,007.34 Acres	Urban Parks	238.58	589.55	0.12%
	Vegetation	25,168.65	62,192.99	13.01%
	Water	16,008.16	39,556.96	8.28%
	Agriculture	30,555.34	75,503.77	8.94%
Lower Weber	Barren/Bedrock	22,492.17	55,579.28	6.58%
(16020102)	**Impervious**	**20,887.21**	**51,613.33**	**6.11%**
	Riparian/Wetland	15,345.94	37,920.59	4.49%
Area:	Snow	26.39	65.20	0.01%
341,957.59 Hectares	Sparse Vegetation	87,259.42	215,622.39	25.52%
844,994.31 Acres	Urban Parks	1,946.19	4,809.14	0.57%
	Vegetation	149,826.26	370,228.19	43.81%
	Water	13,618.67	33,652.41	3.98%
	Agriculture	12,344.32	30,503.43	5.86%
Jordan	Barren/Bedrock	23,500.77	58,071.57	11.16%
(16020204)	**Impervious**	**36,589.96**	**90,415.63**	**17.37%**
	Riparian/Wetland	6,857.49	16,945.19	3.26%
Area:	Snow	502.91	1,242.72	0.24%
210,642.65 Hectares	Sparse Vegetation	46,856.11	115,783.79	22.24%
520,508.52 Acres	Urban Parks	3,250.68	8,032.60	1.54%
	Vegetation	76,366.71	188,705.97	36.25%
	Water	4,373.69	10,807.62	2.08%

Table 4-12. Total area of impervious surface and percent impervious surface for the 14 watersheds. Percentages of impervious surface are highlighted.

SUB-BASIN (HUC 8)	WATERSHED (HUC 10)	TOTAL AREA (Hectares)	TOTAL AREA (Acres)	AREA OF IMPERVIOUS SURACES (Hectares)	AREA OF IMPERVIOUS SURACES (Acres)	PERCENT IMPERVIOUS SURFACE
Lower Bear-Malad (16010204)	Bear River-Frontal Great Salt Lake (1601020405)	91,138.33	225,207.36	1,439.15	3,556.22	1.58%
	Malad River-Bear River (1601020403)	68,111.81	168,307.69	860.47	2,126.28	1.26%
	Whites Valley (1601020404)	34,192.86	84,492.28	504.30	1,246.16	1.47%
Lower Weber (16020102)	Cottonwood Creek-Weber River (1602010204)	70,161.52	173,372.62	3,645.82	9,009.00	5.20%
	East Canyon Creek (1602010201)	61,579.05	152,164.90	1,250.28	3,089.50	2.03%
	Farmington Creek-Frontal Farmington Bay (1602010205)	58,753.38	145,182.54	9,677.34	23,913.18	16.47%
	Headwaters Ogden River (1602010202)	37,139.24	91,772.93	80.62	199.22	0.22%
	Outlet Ogden River (1602010203)	49,160.79	121,478.76	971.88	2,401.57	1.98%
	Third Salt Creek-Frontal Great Salt Lake (1602010207)	31,531.25	77,915.30	629.67	1,555.94	2.00%
	Weber River-Frontal Great Salt Lake (1602010206)	33,632.37	83,107.27	4,631.60	11,444.91	13.77%
Jordan (16020204)	Big Cottonwood Creek-Jordan River (1602020402)	45,771.52	113,103.71	8,029.54	19,841.39	17.54%
	Bingham Creek-Jordan River (1602020401)	51,429.98	127,086.06	10,191.12	25,182.76	19.82%
	Jordan River-Frontal Great Salt Lake (1602020404)	61,582.10	152,172.44	7,936.64	19,611.83	12.89%
	Mill Creek-Jordan River (1602020403)	51,859.05	128,146.31	10,432.67	25,779.65	20.12%

Table 4-13. Percent impervious surface for watersheds and associated ICM classifications.

SUB-BASIN (HUC 8)	WATERSHED (HUC 10)	PERCENT IMPERVIOUS SURFACE	ORIGINAL ICM CLASSIFICATION (Schueler, 1994; CWP, 2003)	REFORMULATED ICM CLASSICATION (Schueler et al., 2009)
Lower Bear-Malad (16010204)	Bear River-Frontal Great Salt Lake (1601020405)	1.58%	Sensitive	Sensitive
	Malad River-Bear River (1601020403)	1.26%	Sensitive	Sensitive
	Whites Valley (1601020404)	1.47%	Sensitive	Sensitive
Lower Weber (16020102)	Cottonwood Creek-Weber River (1602010204)	5.20%	Sensitive	Transition to Impacted
	East Canyon Creek (1602010201)	2.03%	Sensitive	Sensitive
	Farmington Creek-Frontal Farmington Bay (1602010205)	16.47%	Impacted	Impacted
	Headwaters Ogden River (1602010202)	0.22%	Sensitive	Sensitive
	Outlet Ogden River (1602010203)	1.98%	Sensitive	Sensitive
	Third Salt Creek-Frontal Great Salt Lake (1602010207)	2.00%	Sensitive	Sensitive
	Weber River-Frontal Great Salt Lake (1602010206)	13.77%	Impacted	Impacted
Jordan (16020204)	Big Cottonwood Creek-Jordan River (1602020402)	17.54%	Impacted	Impacted
	Bingham Creek-Jordan River (1602020401)	19.82%	Impacted	Impacted
	Jordan River-Frontal Great Salt Lake (1602020404)	12.89%	Impacted	Impacted
	Mill Creek-Jordan River (1602020403)	20.12%	Impacted	Transition to Non-Supporting

Figures

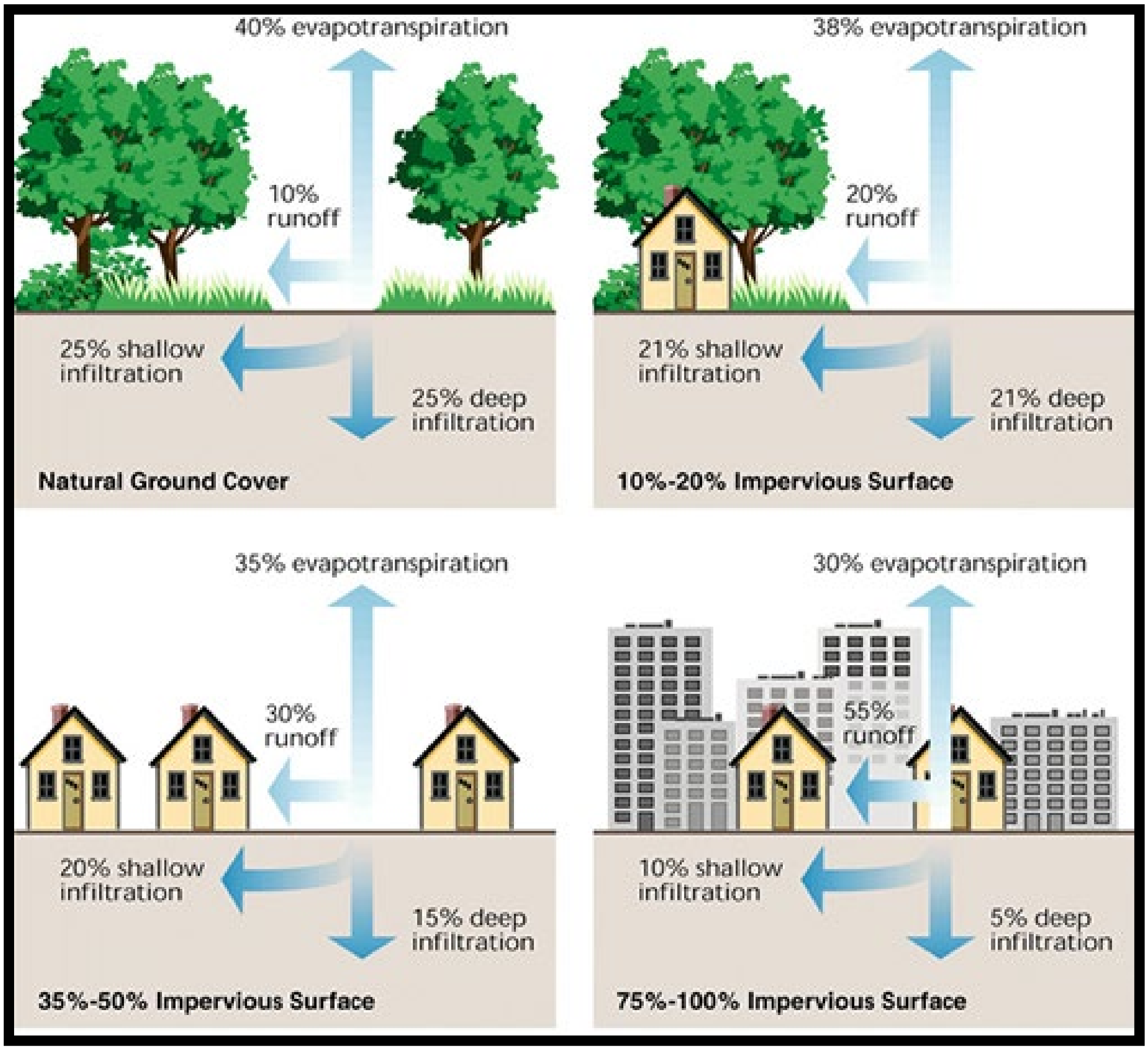

Figure 4-1. Relationship between impervious cover and surface runoff. Impervious cover in a watershed results in increased surface runoff. As little as 10 percent impervious surface cover in a watershed can result in stream degradation. Source: USDA Natural Resource Conservation Service, Federal Stream Corridor Restoration Handbook (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/water/manage/restoration/?cid=stelprdb1044678).

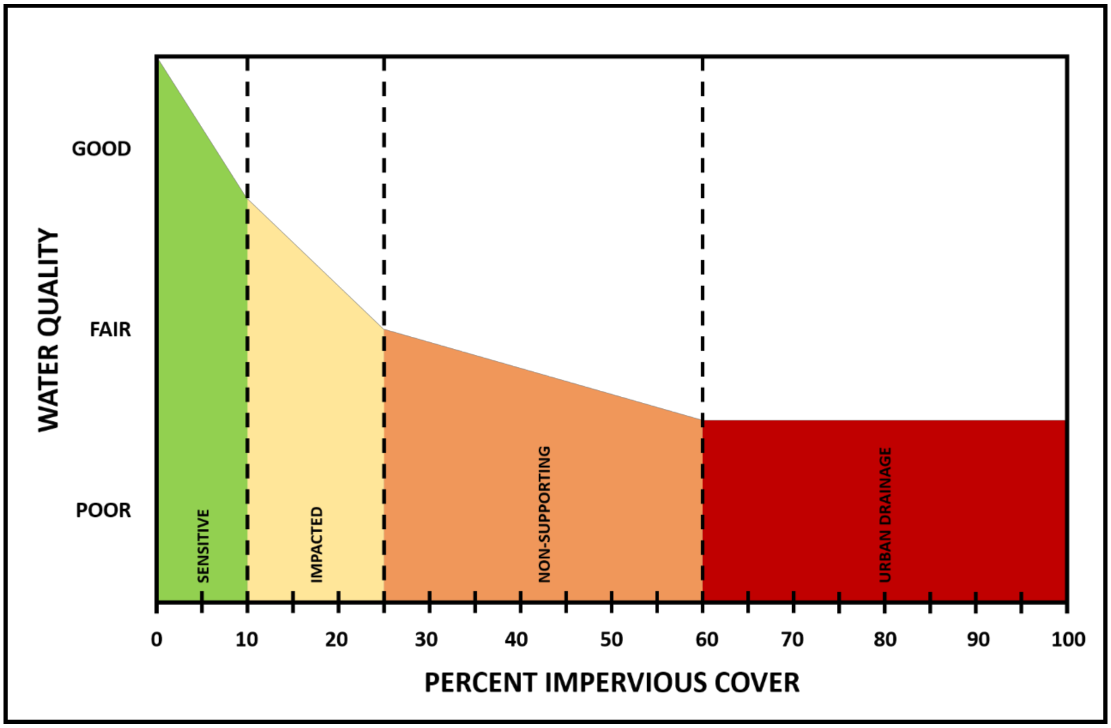

Figure 4-2. Original Impervious Cover Model (ICM). Adapted from Schueler, 1994.

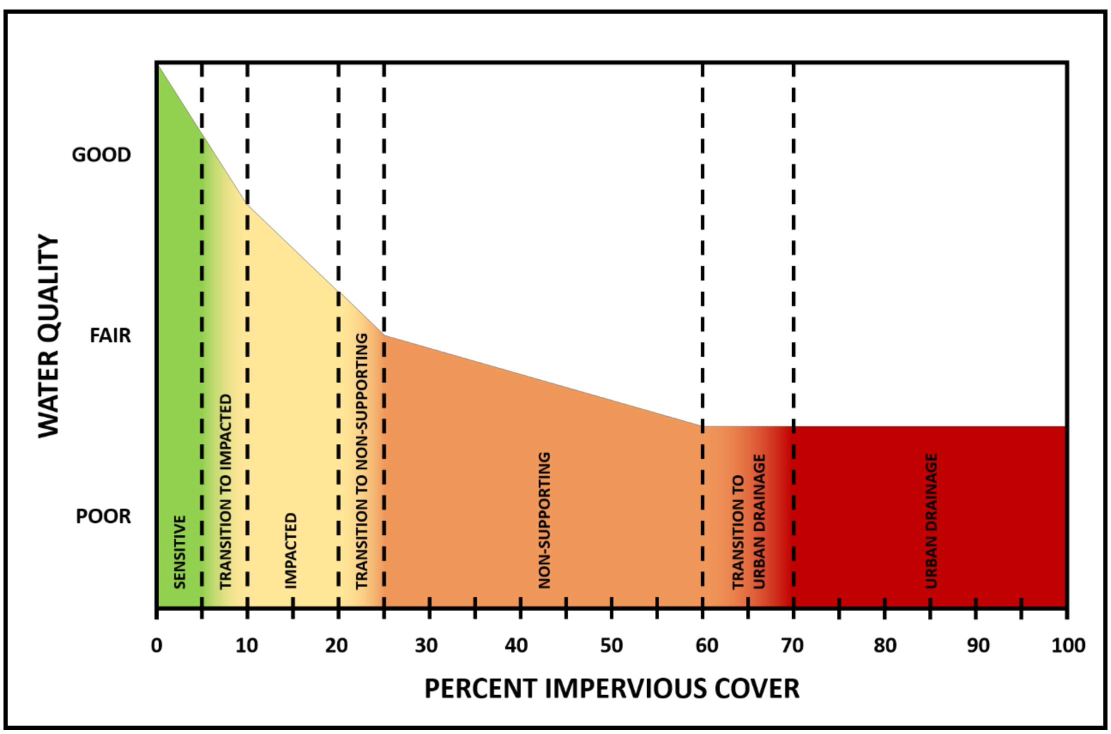

Figure 4-3. Reformulated Impervious Cover Model (ICM). Adapted from Schueler et al., 2009.

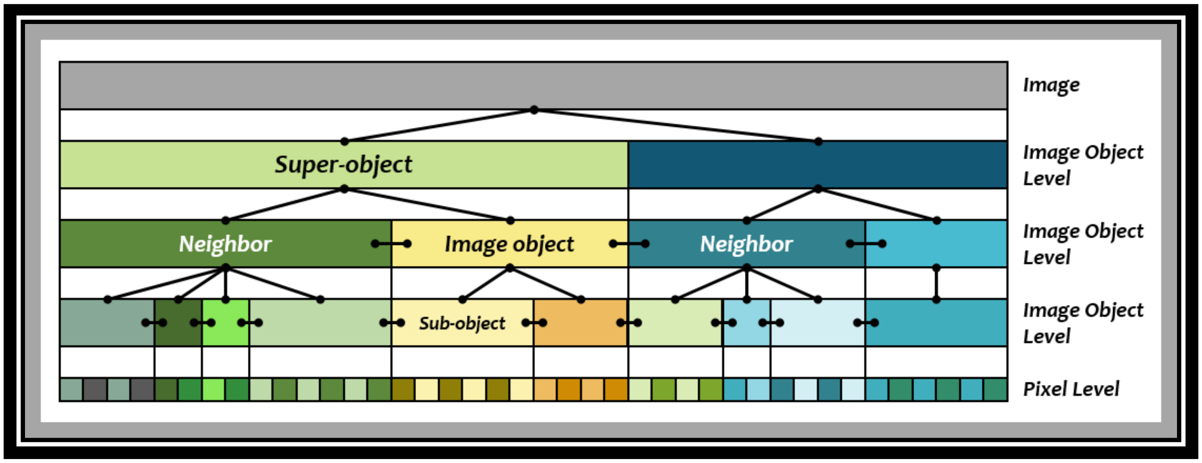

Figure 4-4 Object-based image analysis image object hierarchy and relationships. Adapted from Definiens Developer User Guide.

Figure 4-5. Elements of object-based image analysis. Adapted from O'Neil-Dunne, 2009.

Figure 4-6. Study area. Data source: USGS National Map Hydrography Viewer. Imagery source: Esri Basemaps.

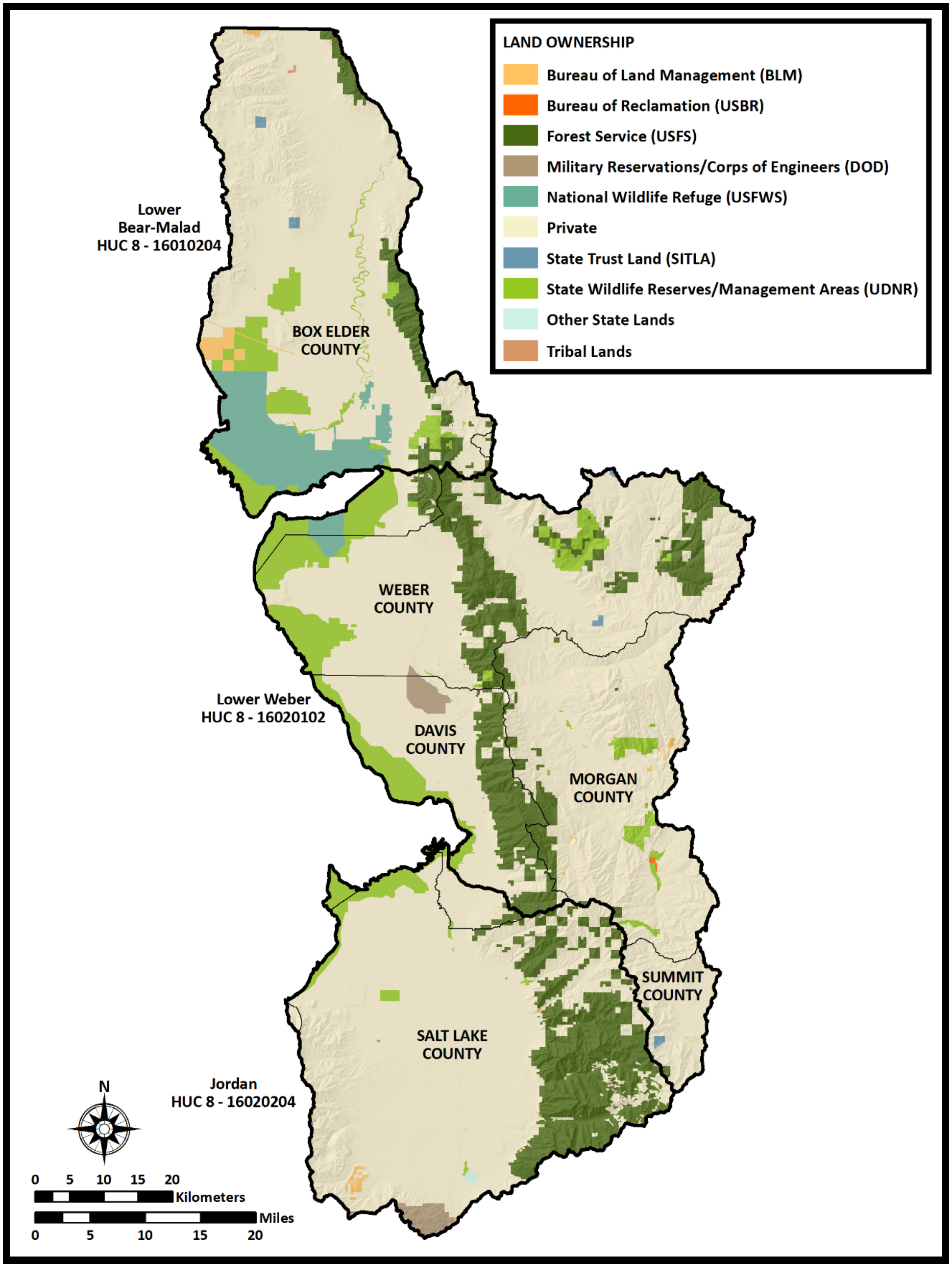

Figure 4-7. Land ownership within the study area. Data source: Utah AGRC.

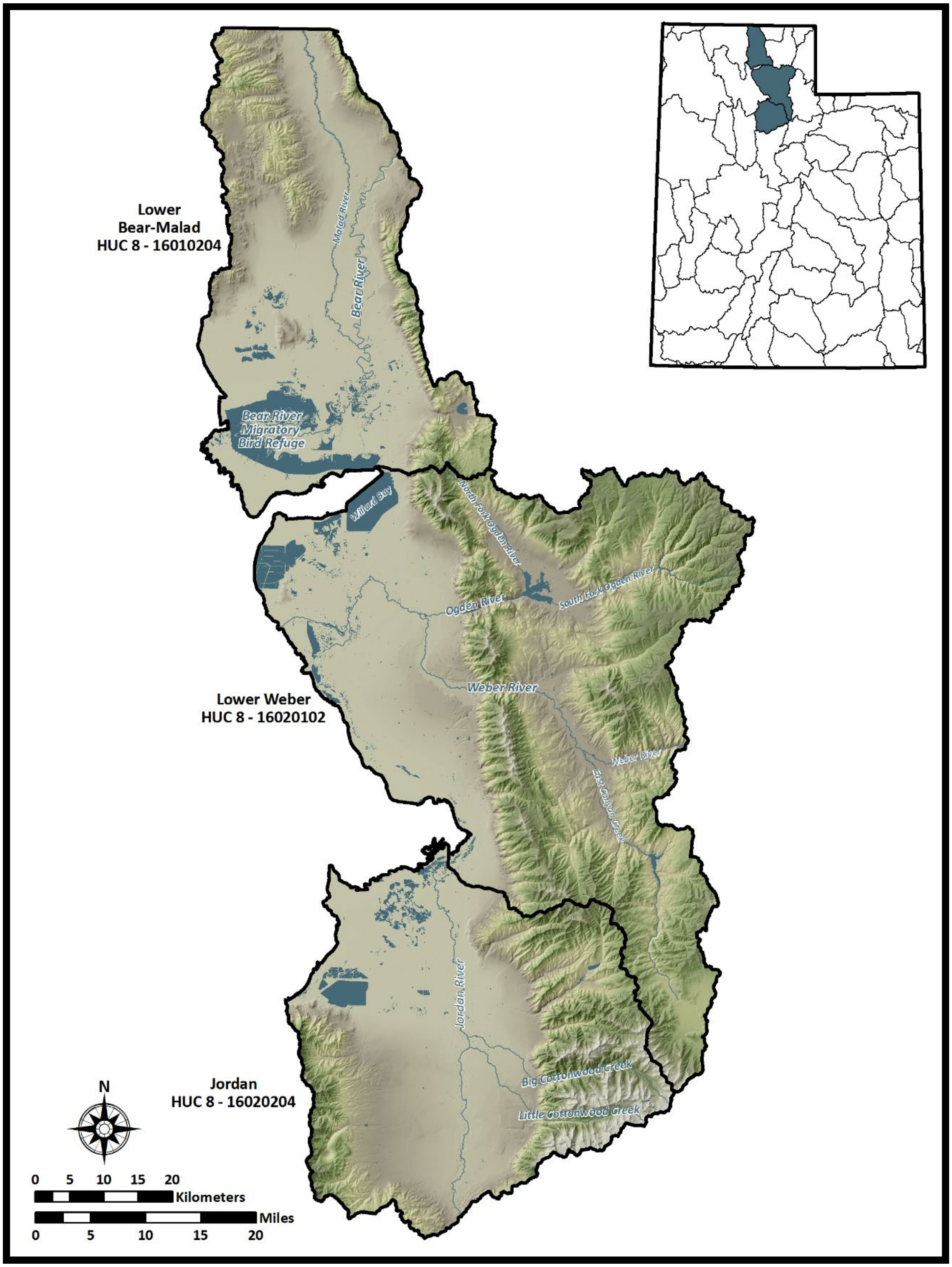

Figure 4-8. Primary surface water features within the study area. Data sources: Utah AGRC and USGS National Map.

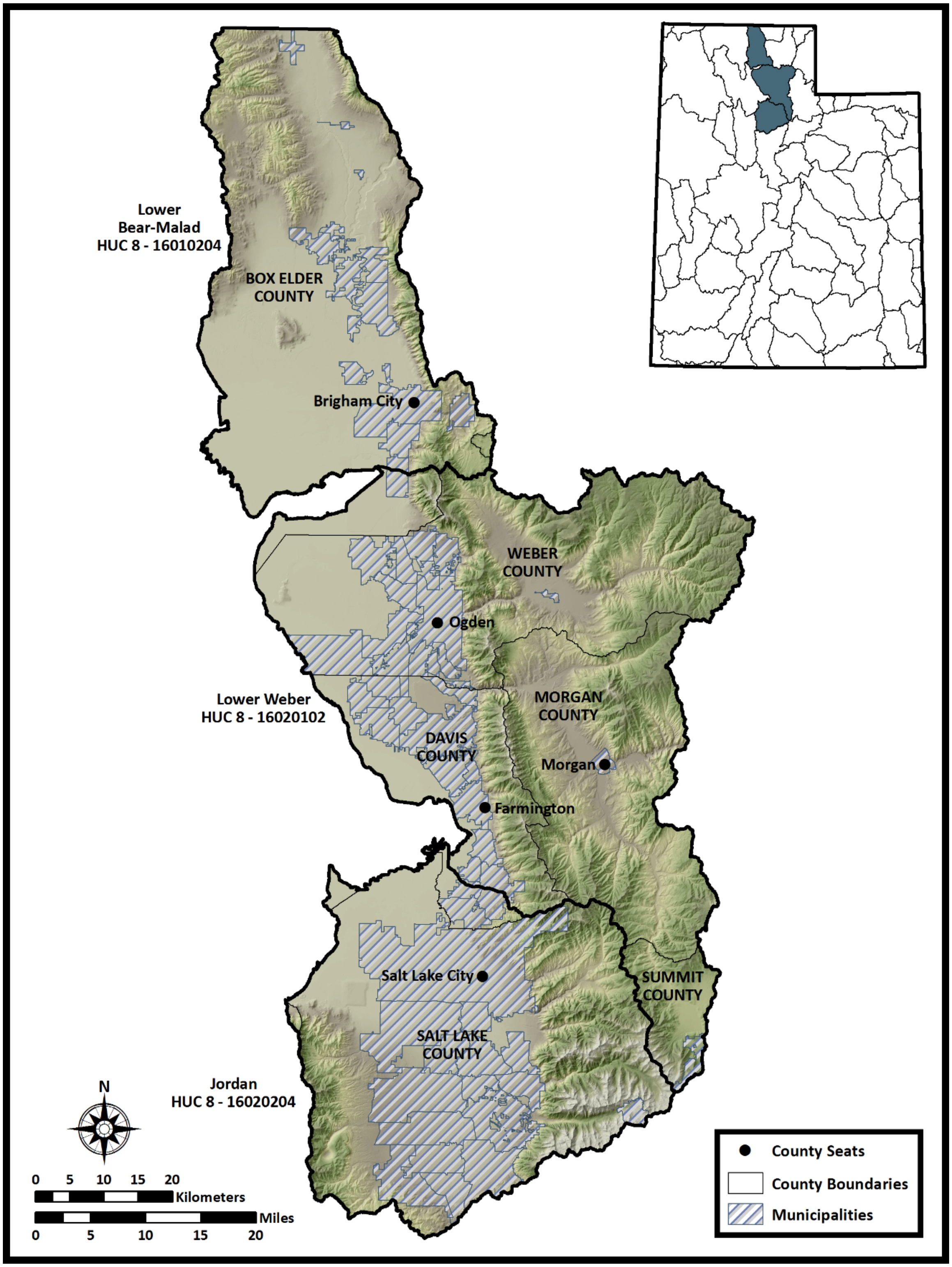

Figure 4-9. Municipalities within the study area. Data sources: Utah AGRC and USGS National Map.

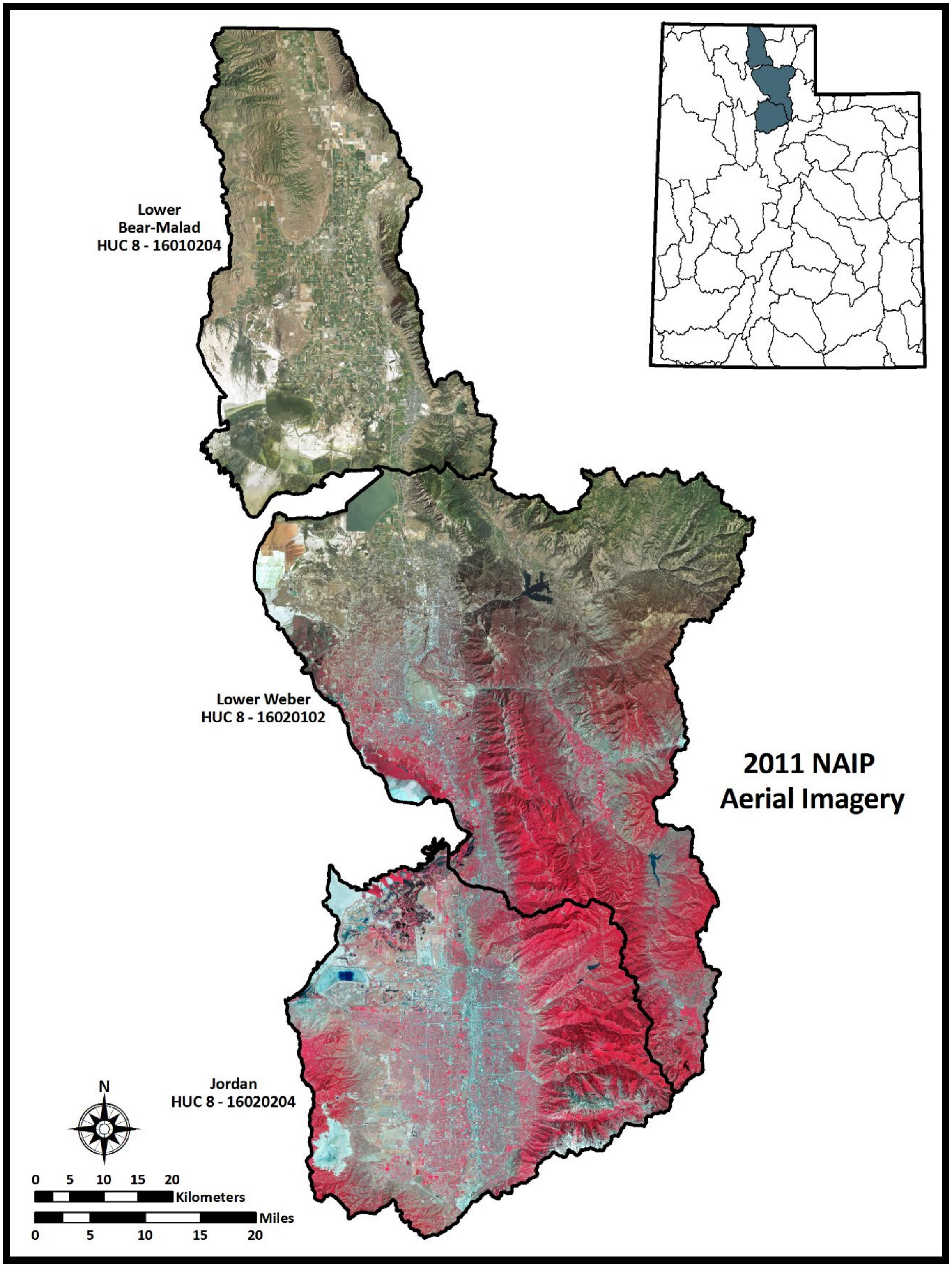

Figure 4-10. 2011 National Agriculture Imagery Program (NAIP) aerial imagery shown in a gradient from natural color (top) to color infrared (bottom). Data source: Utah AGRC.

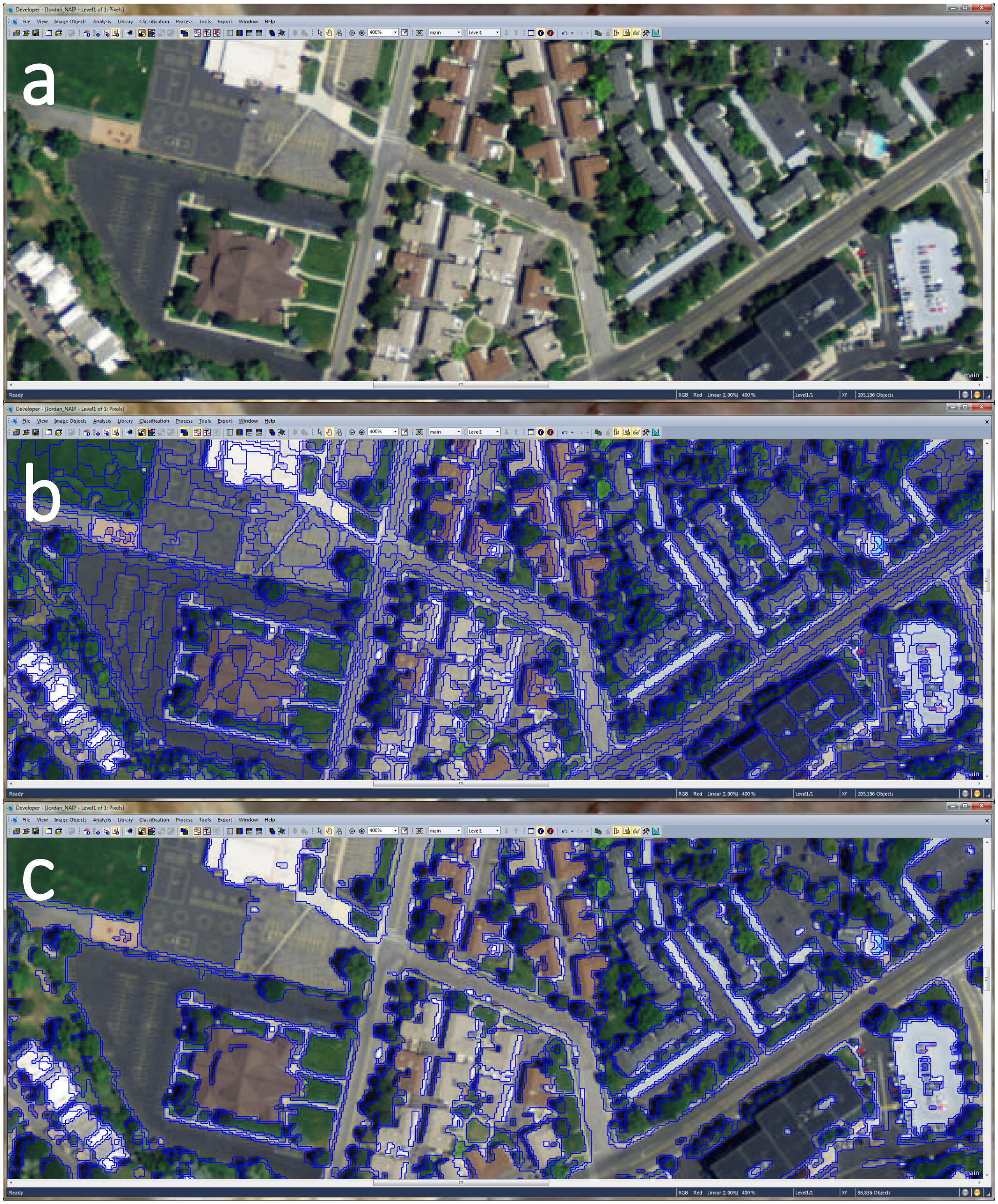

Figure 4-11. Segmentation process in Trimble eCognition: (a) 2011 NAIP aerial imagery; (b) multiresolution segmentation; and (c) spectral difference segmentation.

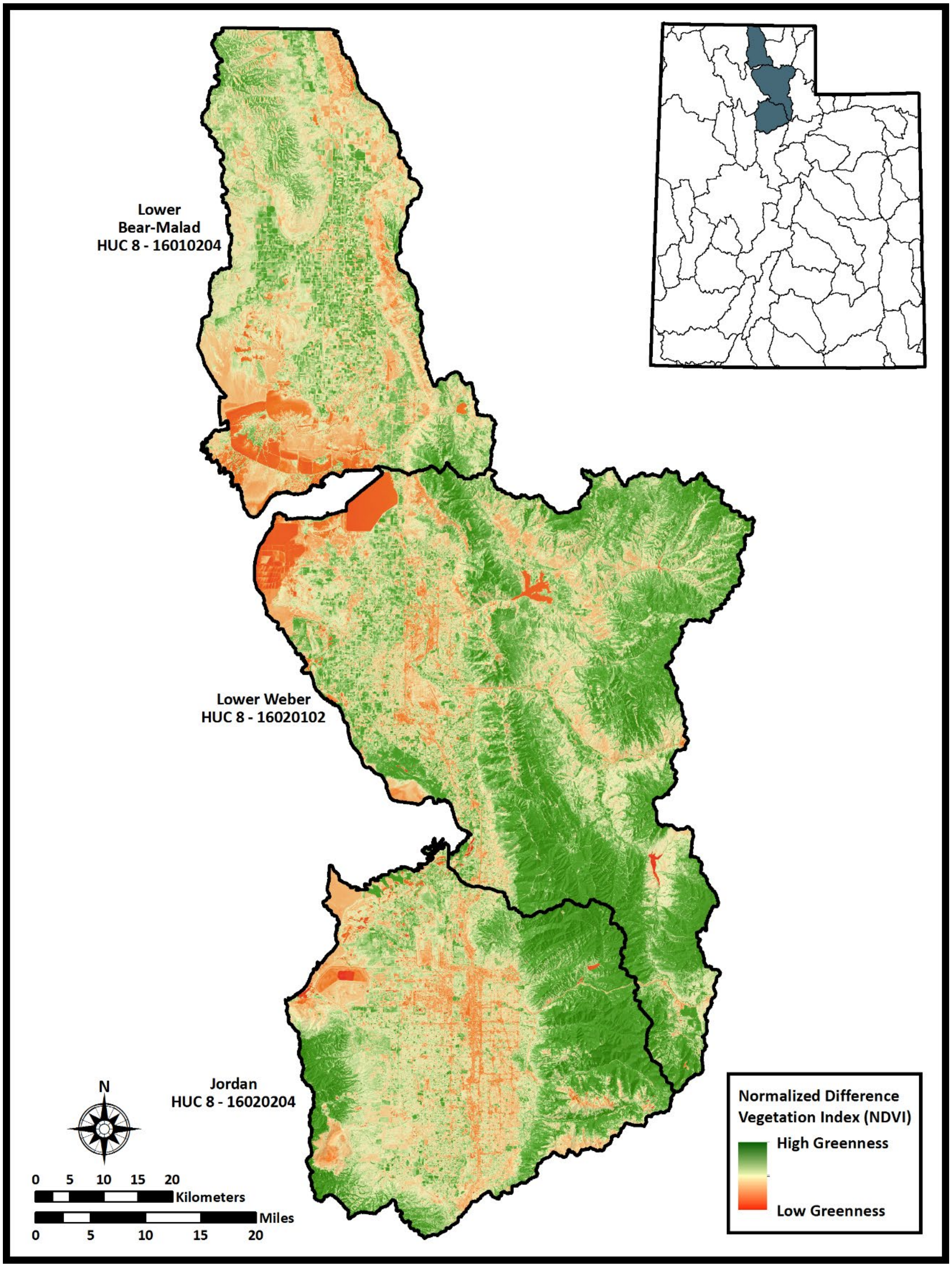

Figure 4-12. Normalized difference vegetation index (NDVI).

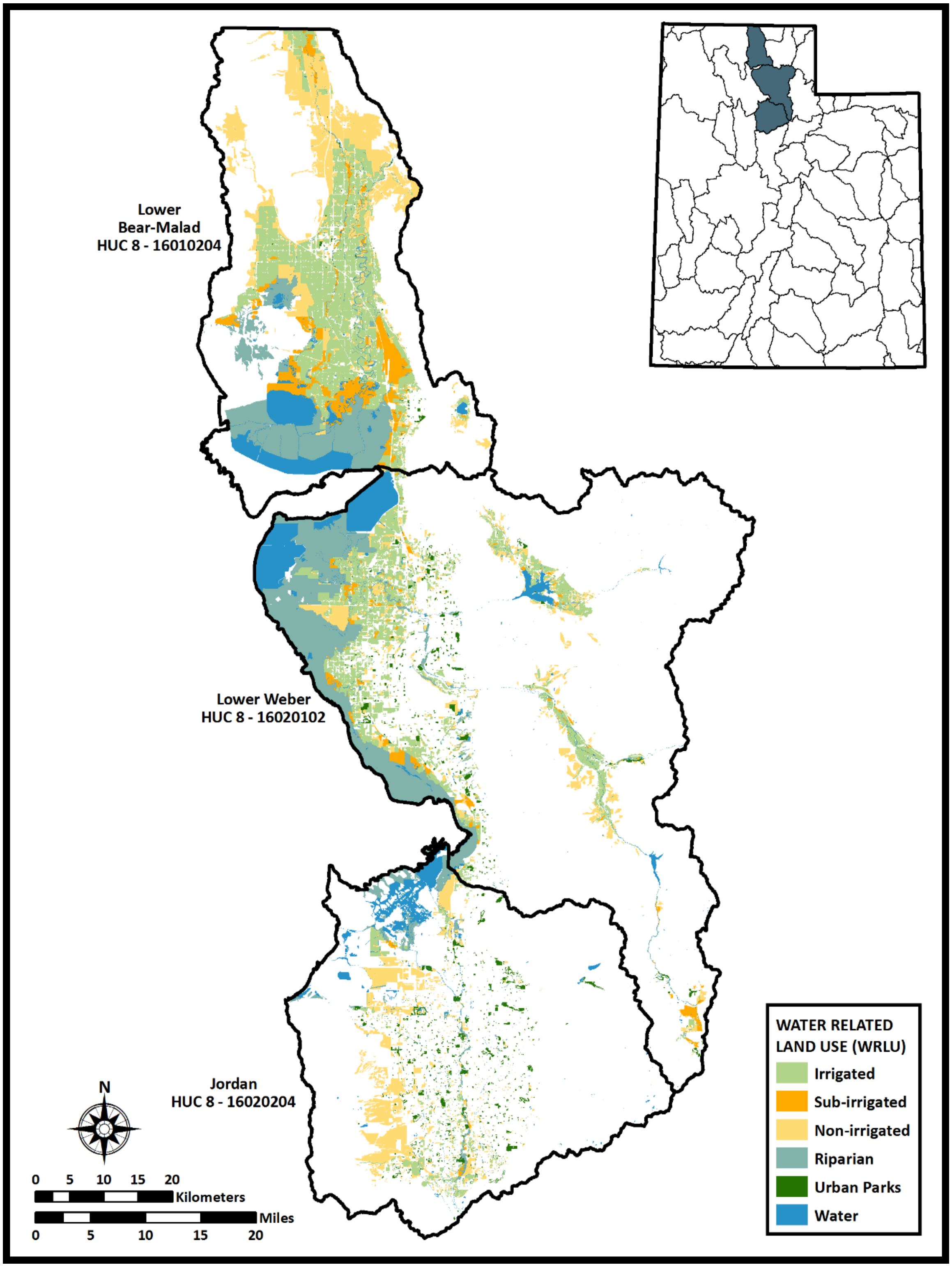

Figure 4-13. Water Related Land Use (WRLU) within the study area. Data source: Utah AGRC.

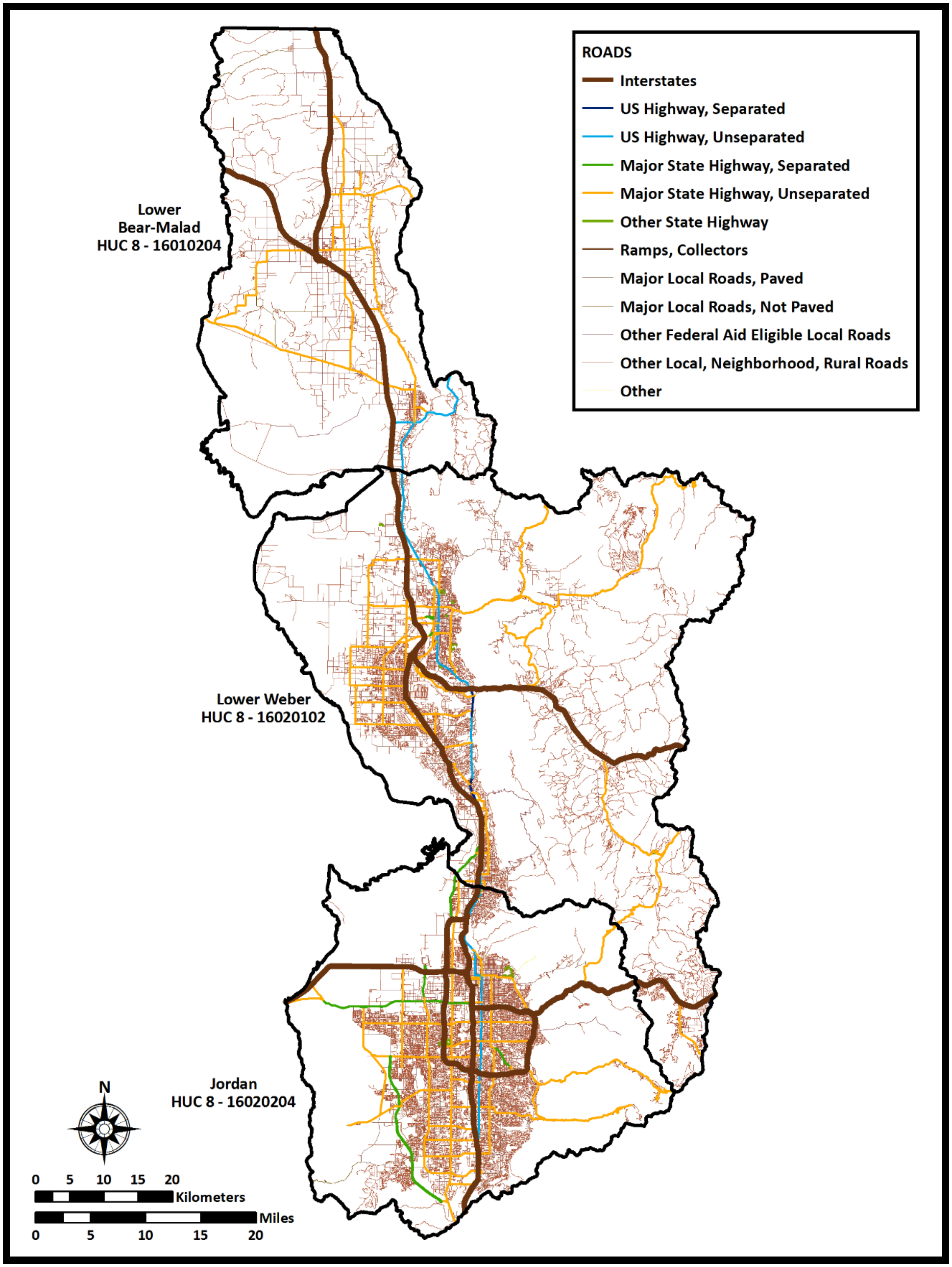

Figure 4-14. Road centerline data within the study area. Data source: Utah AGRC.

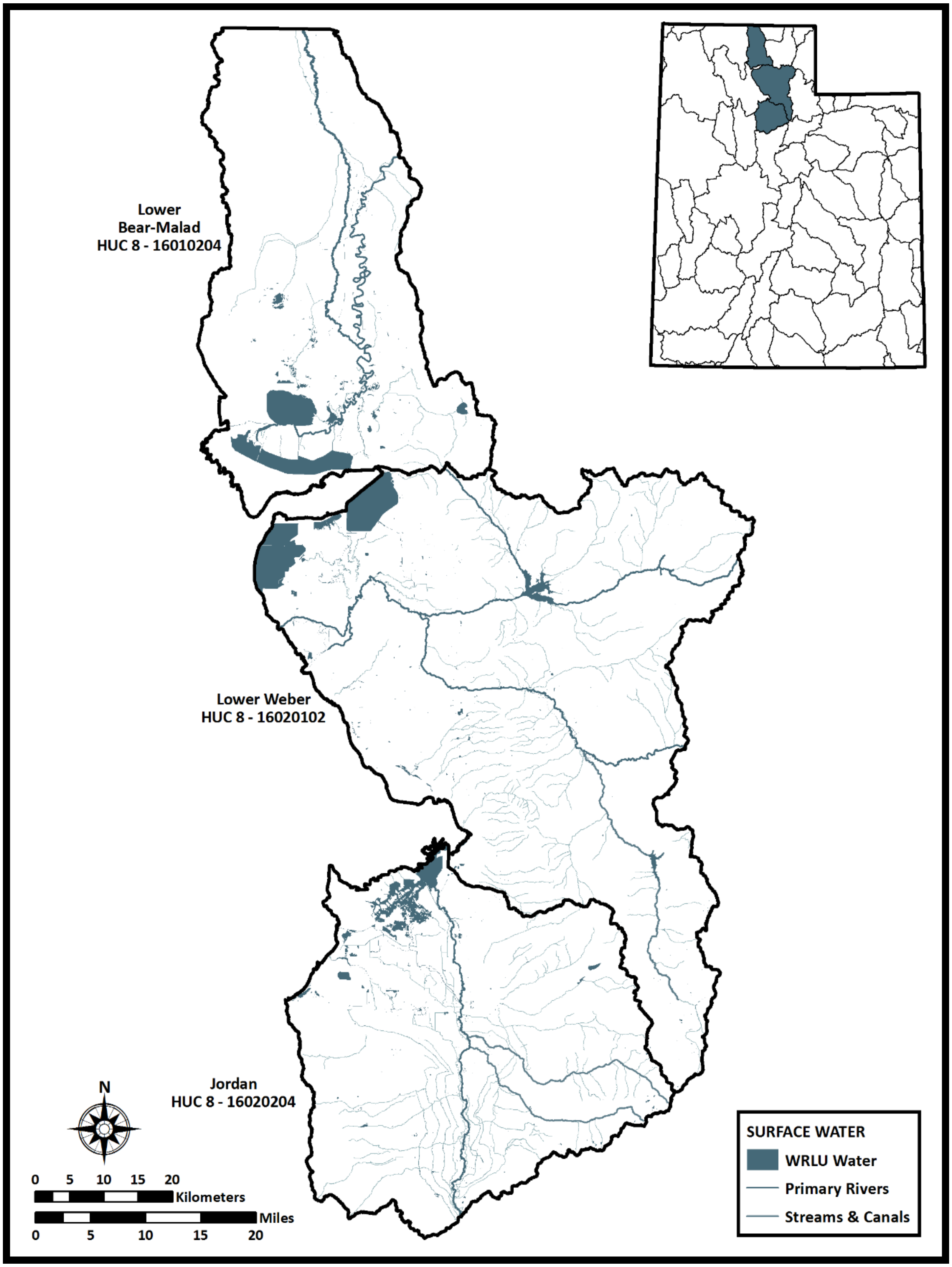

Figure 4-15. Water features from the WRLU data and primary rivers, streams, and canals. Data source: Utah AGRC.

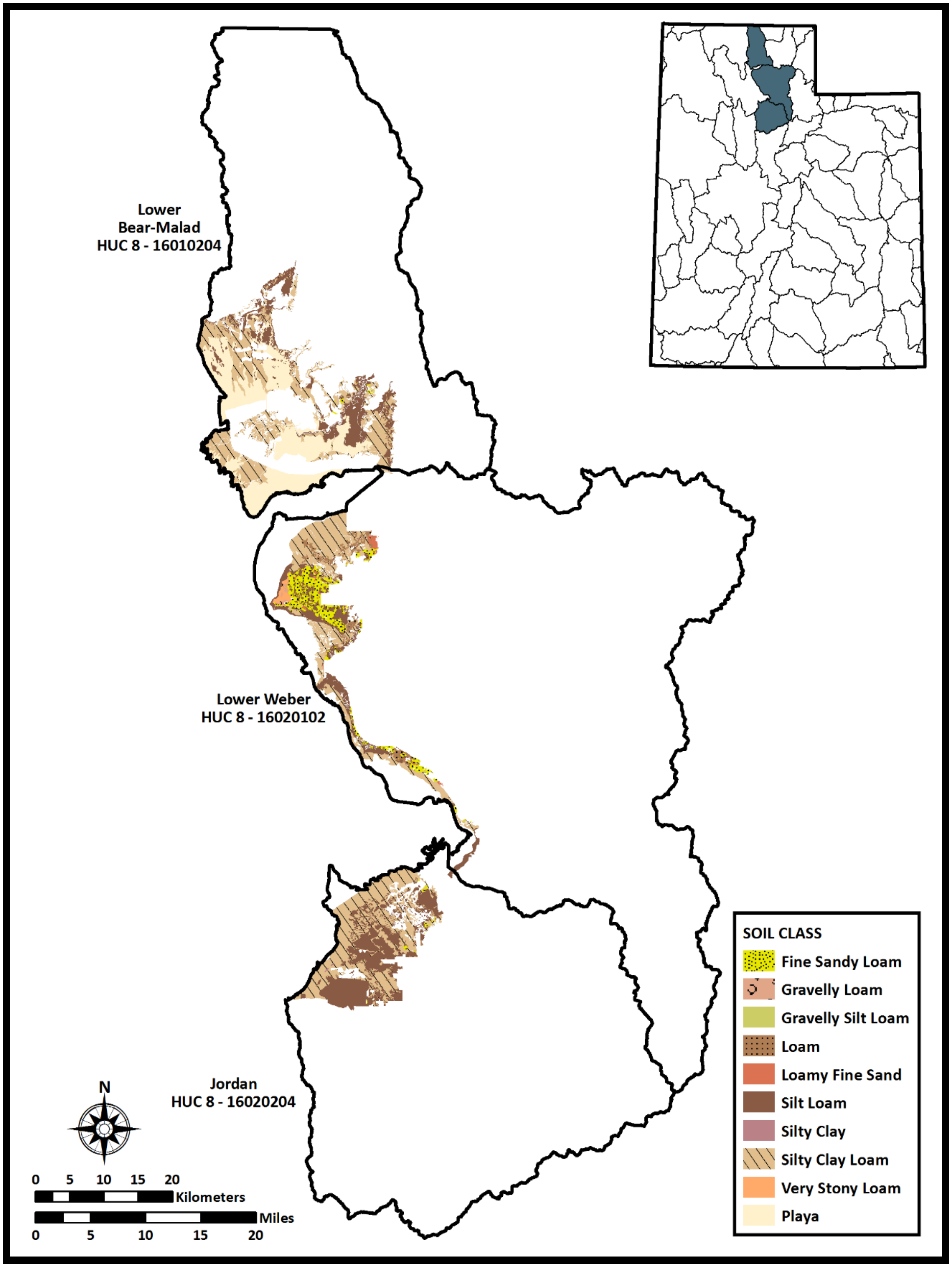

Figure 4-16. Soils adjacent to the Great Salt Lake with high brightness values. Data source: Utah AGRC.

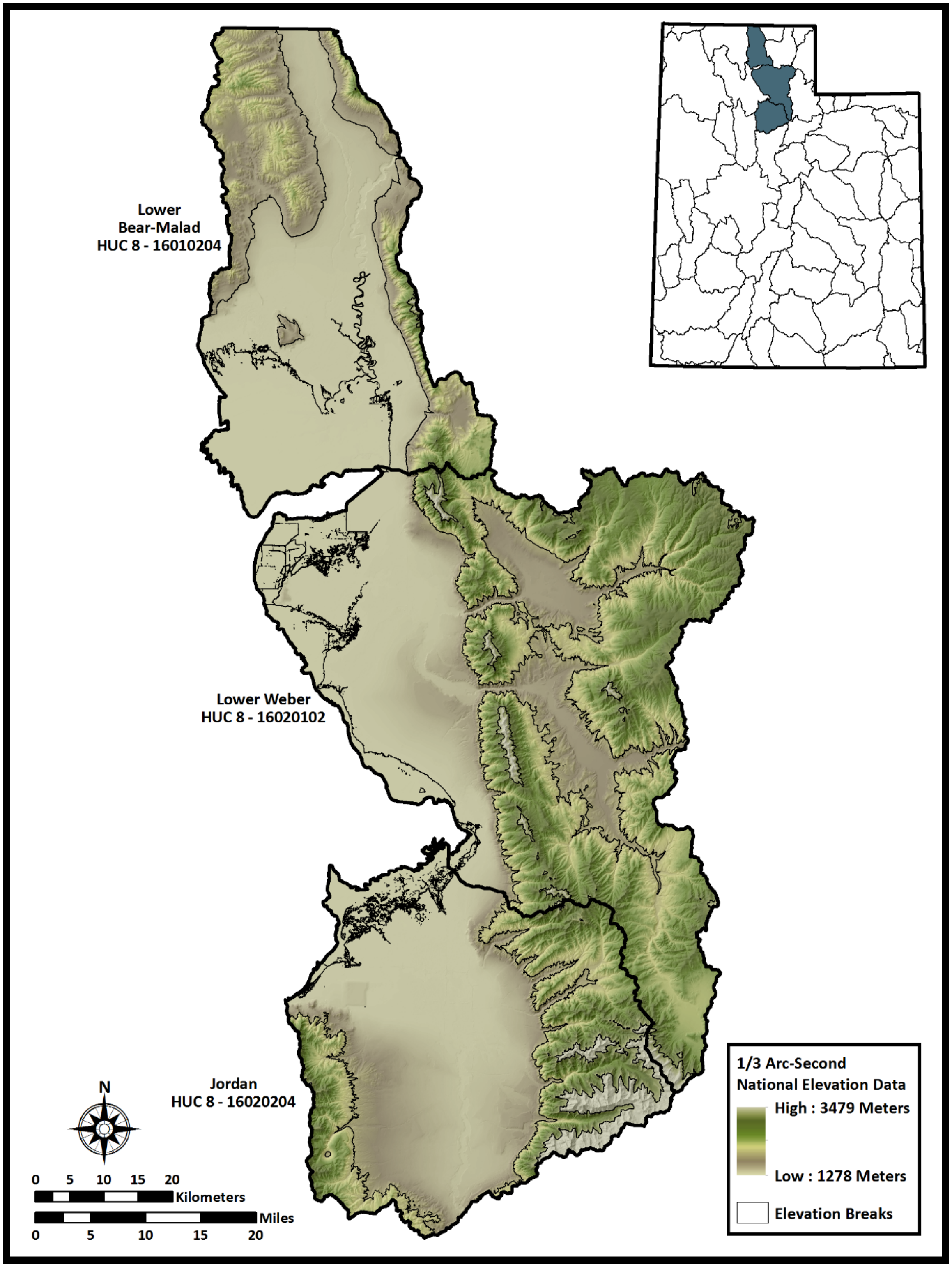

Figure 4-17. 1/3 Arc-second National Elevation Data (NED) and elevation breaks. Data source: USGS National Map.

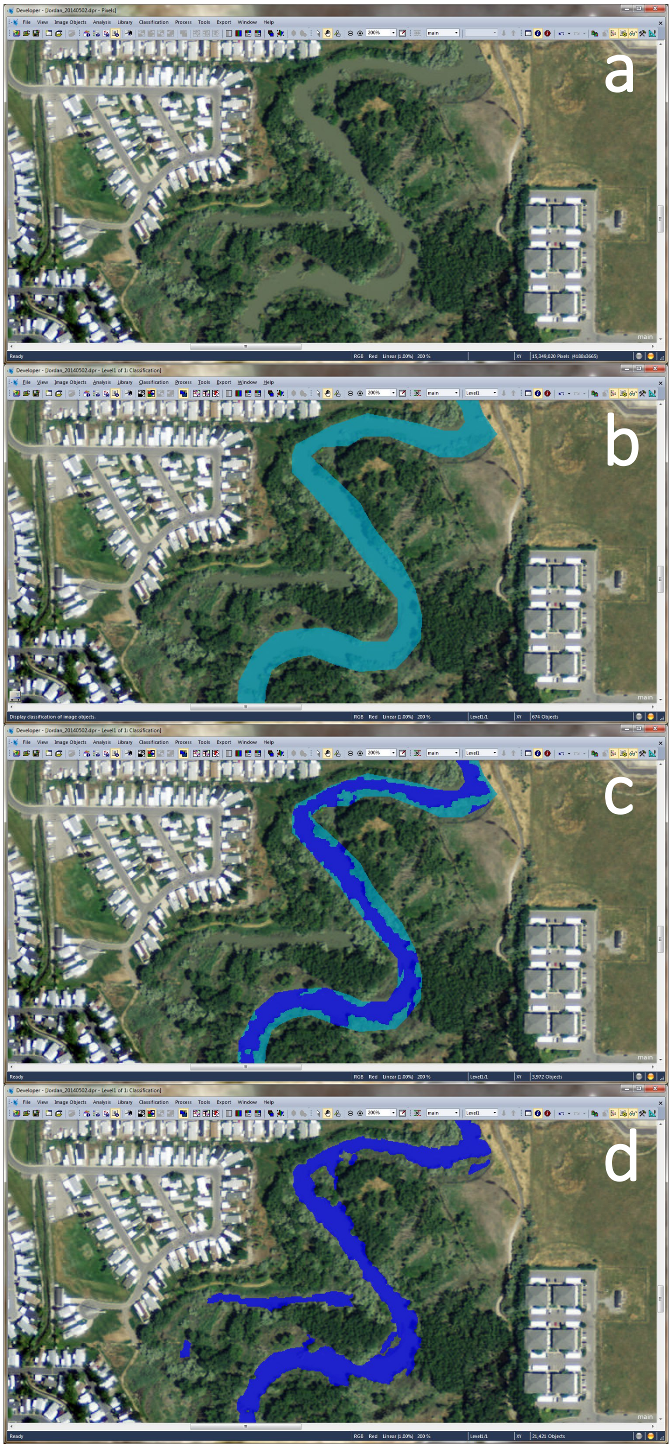

Figure 4-18. Example of how ancillary data sets were incorporated into the eCognition rule set development process: (a) 2011 NAIP imagery; (b) water features from WRLU data were imported into eCognition; (c) segmentation algorithms were applied and rules were developed to provide for more accurate representations of water features; and (d) non-water features were removed from the results and additional rules were developed to identify water features that were not captured in the WRLU data.

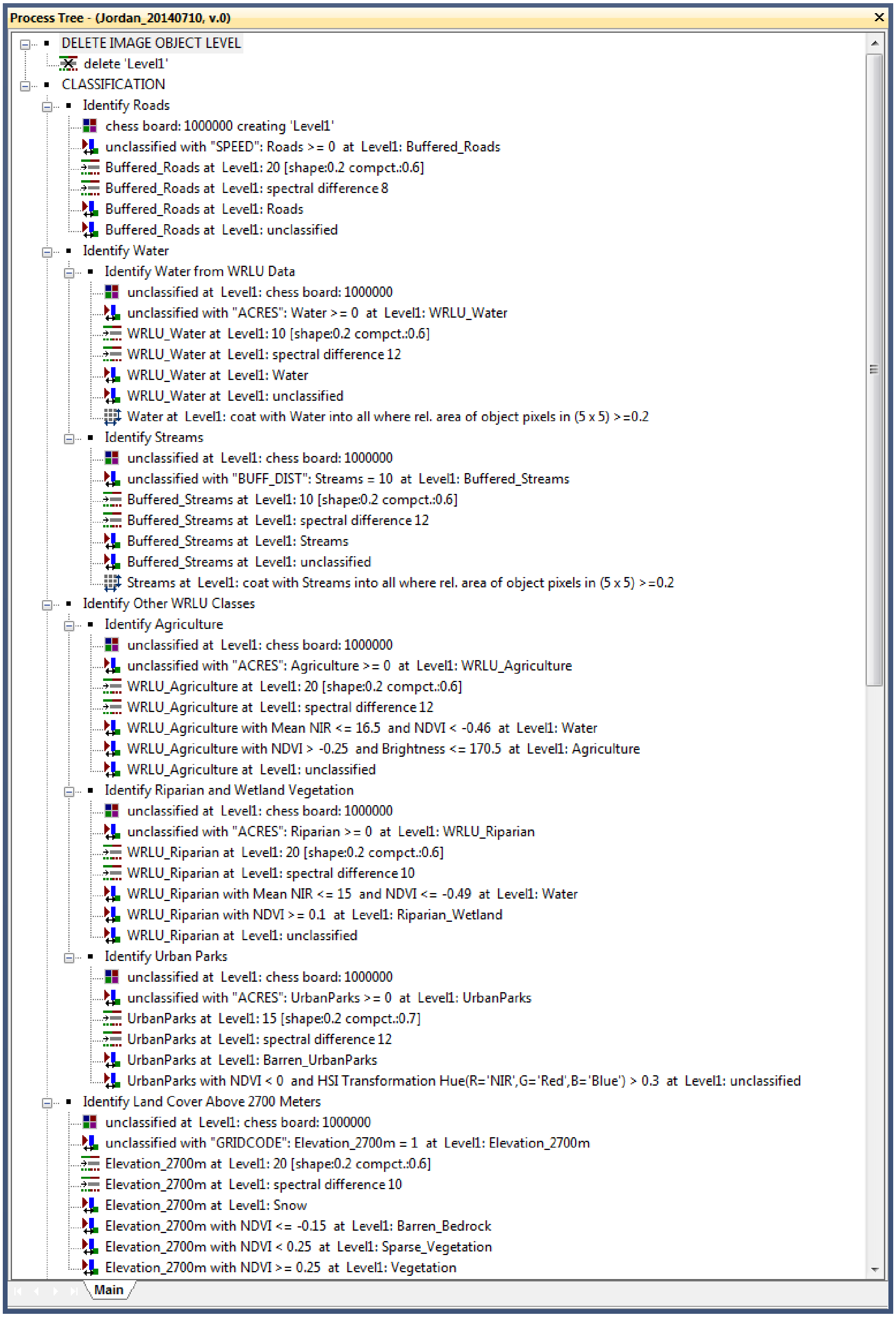

Figure 4-19. Final eCognition rule set for Jordan sub-basin (continued on next page).

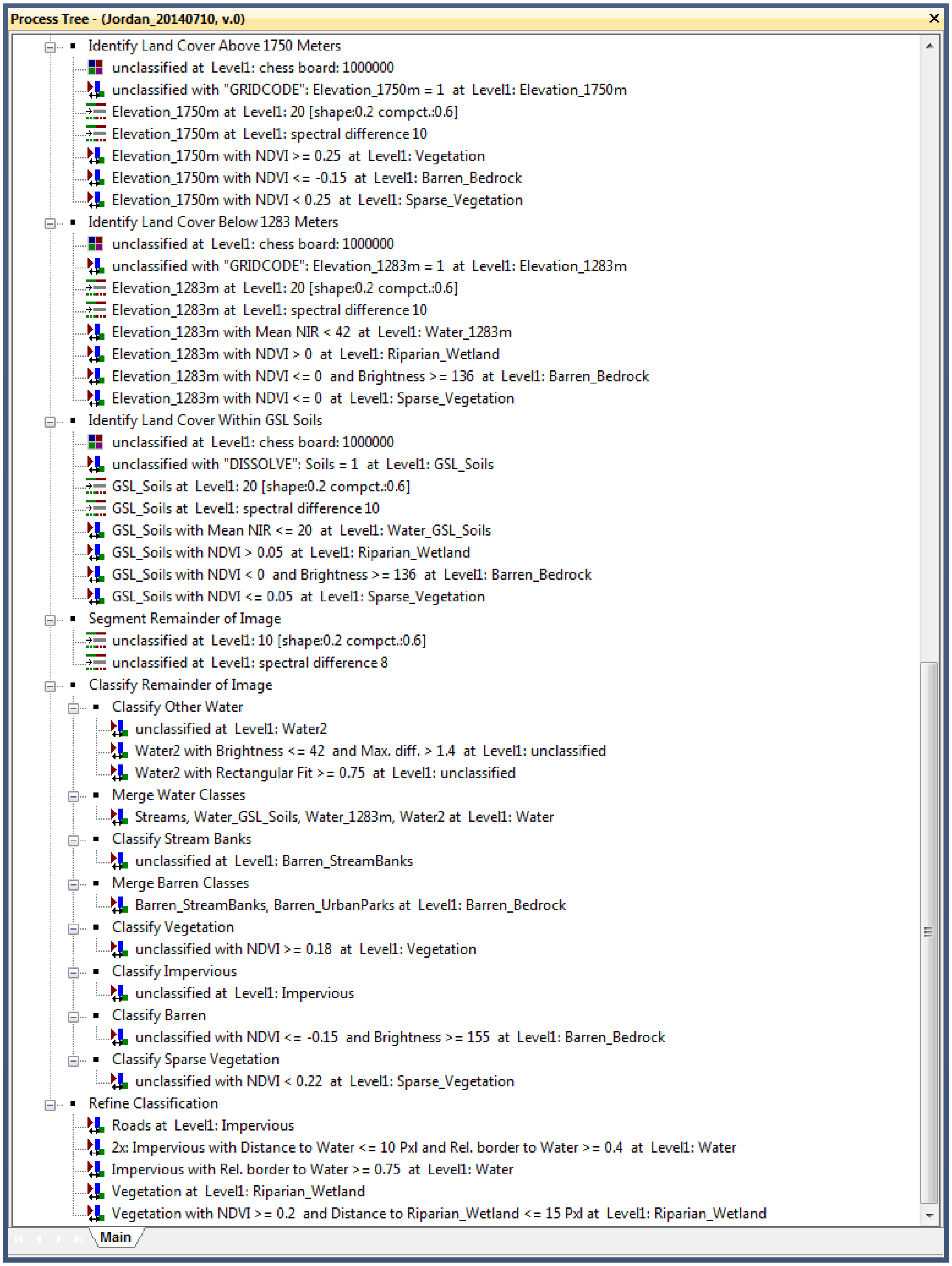

Figure 4-19 (continued). Final eCognition rule set for Jordan sub-basin.

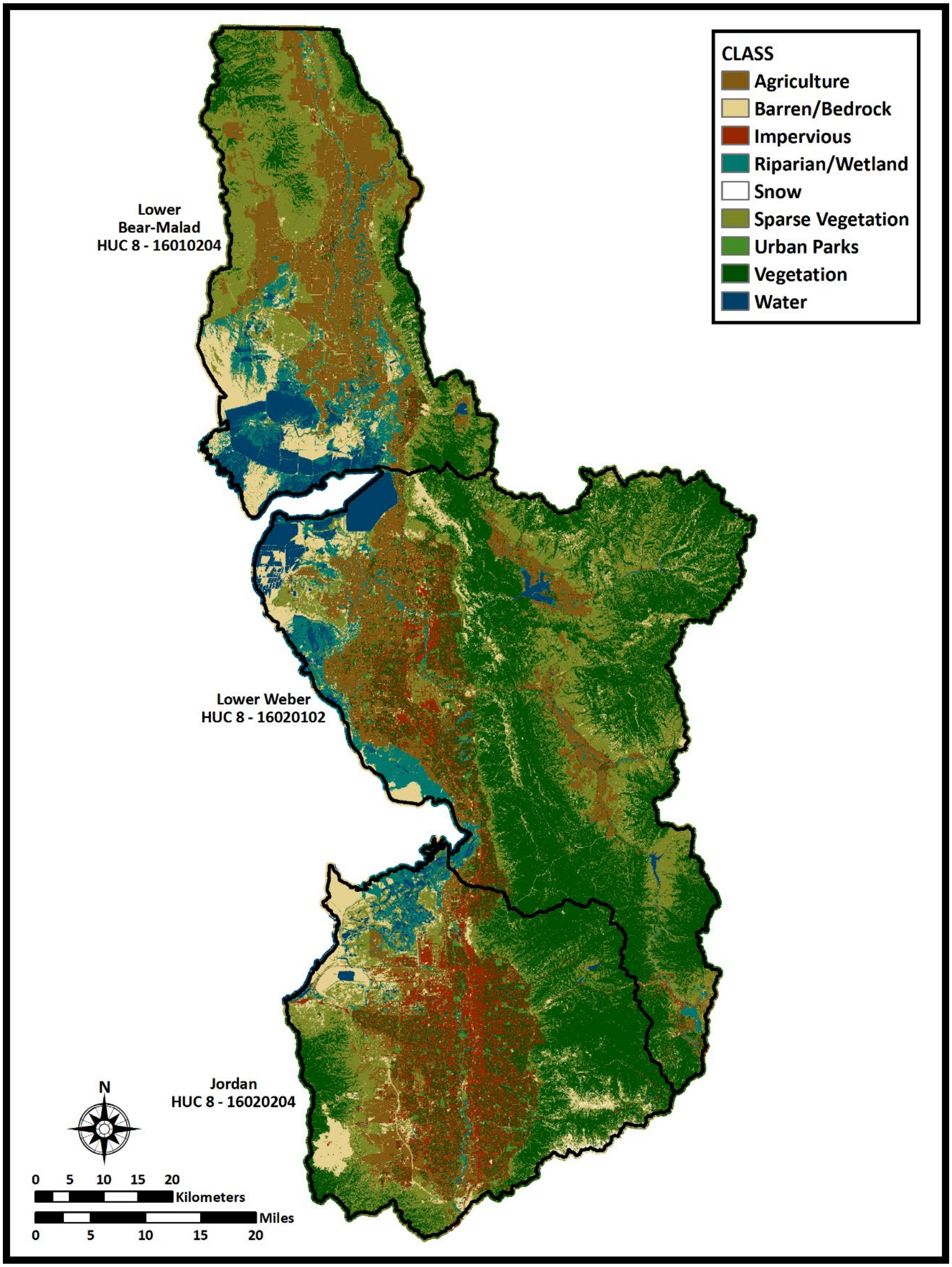

Figure 4-20. LULC classification results for the three sub-basins.

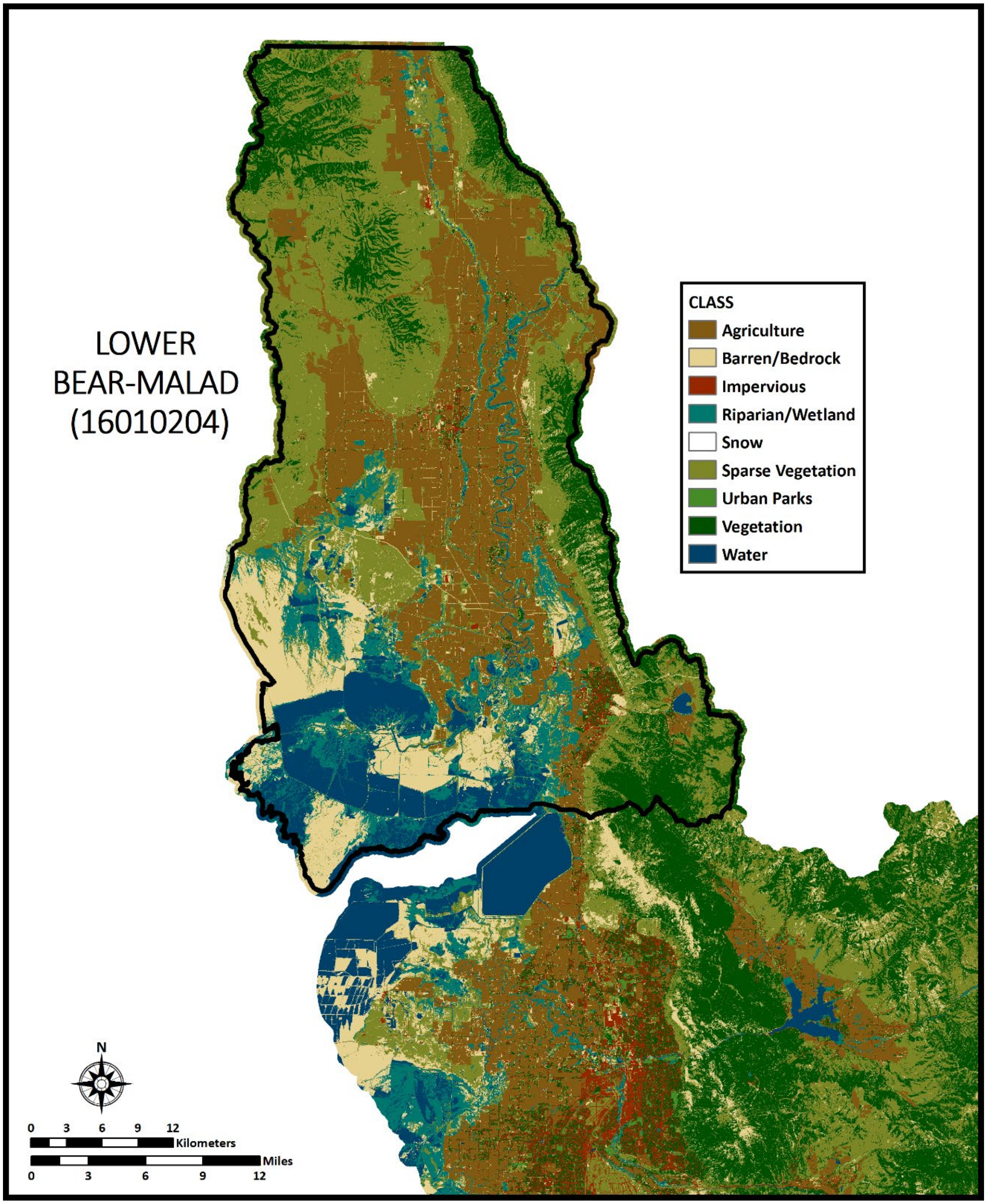

Figure 4-21. LULC classification results for Lower Bear-Malad sub-basins.

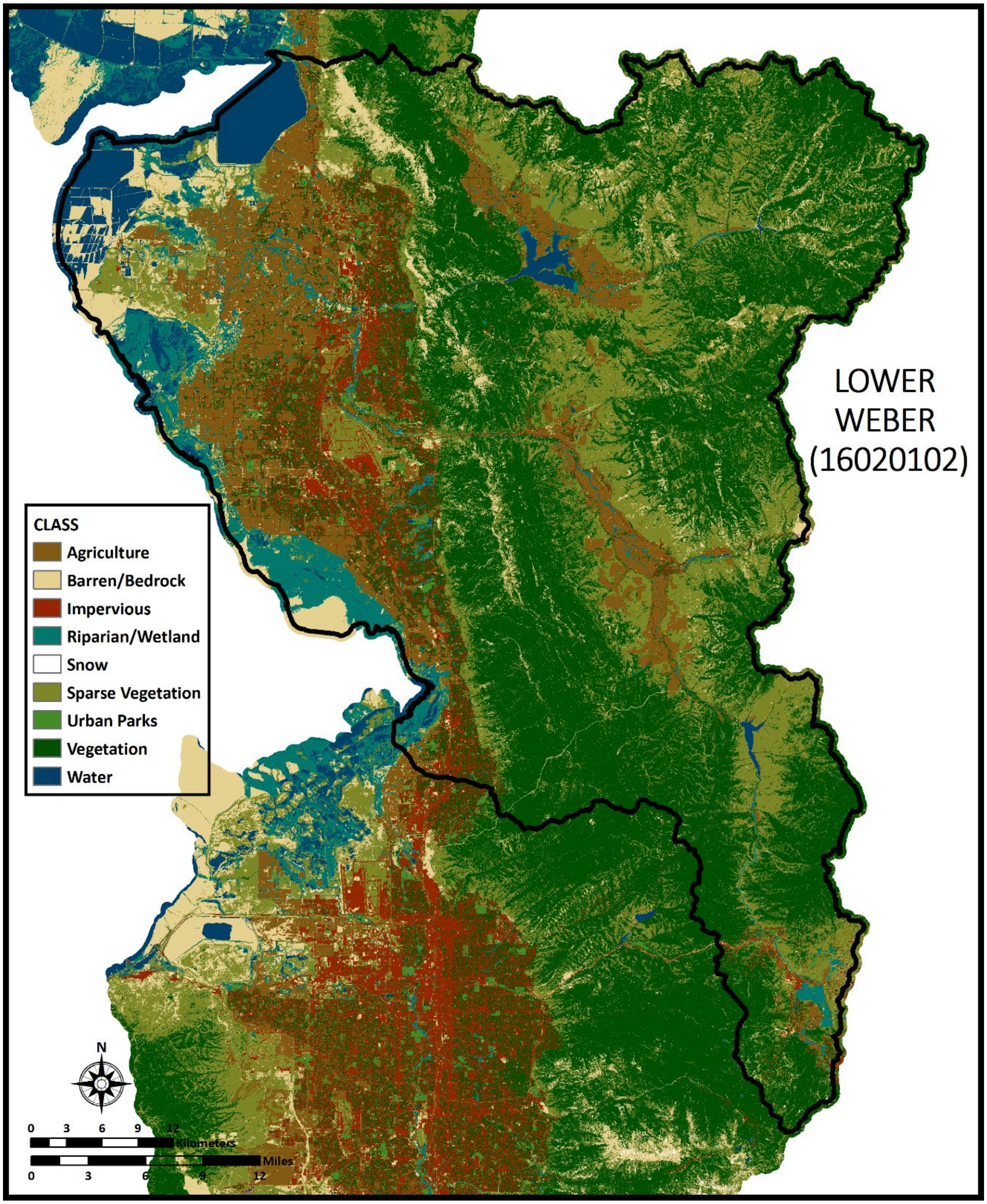

Figure 4-22. LULC classification results for Lower Weber sub-basins.

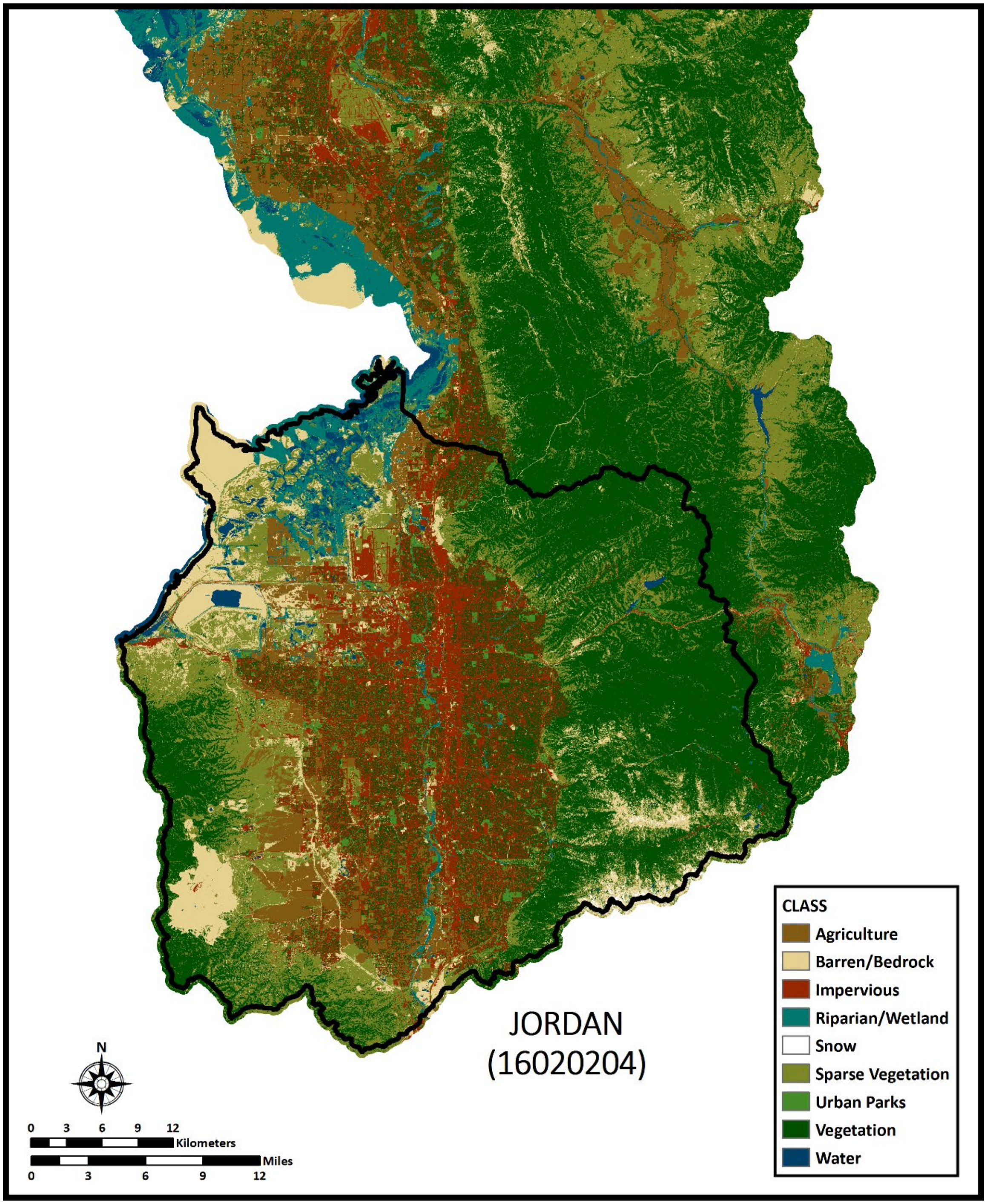

Figure 4-23. LULC classification results for Jordan sub-basins.

Figure 4-24. Detailed views of the three sub-basins.

Figure 4-25. Watersheds (HUC 10) within the study area. Data source: USGS National Map Hydrography Viewer. Imagery source: Esri Basemaps.

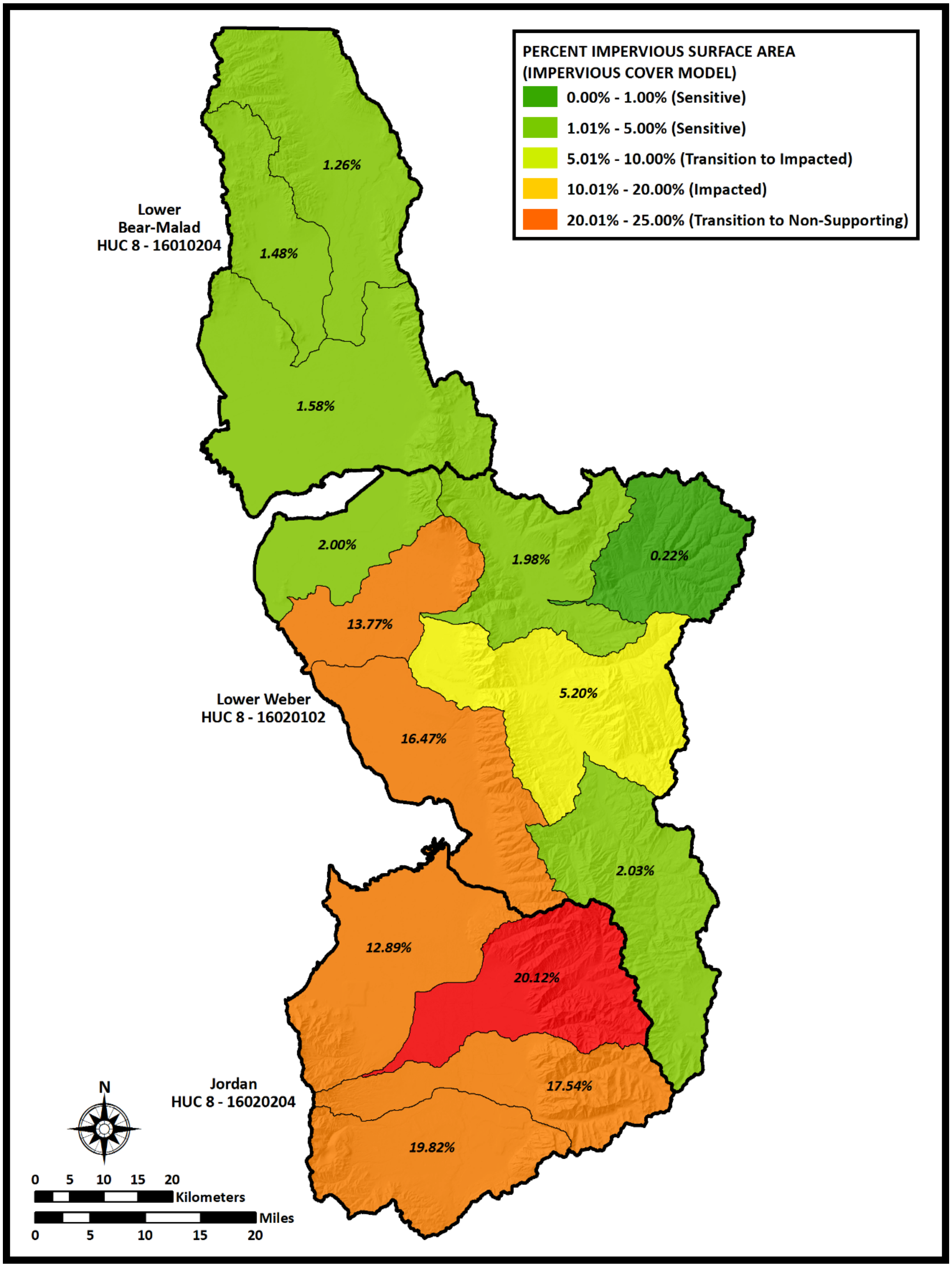

Figure 4-26. Impervious Cover Model (ICM) estimates for watersheds within the study area (Schueler, -1994; Schueler et al., 2009). Data source: USGS National Map Hydrography Viewer.

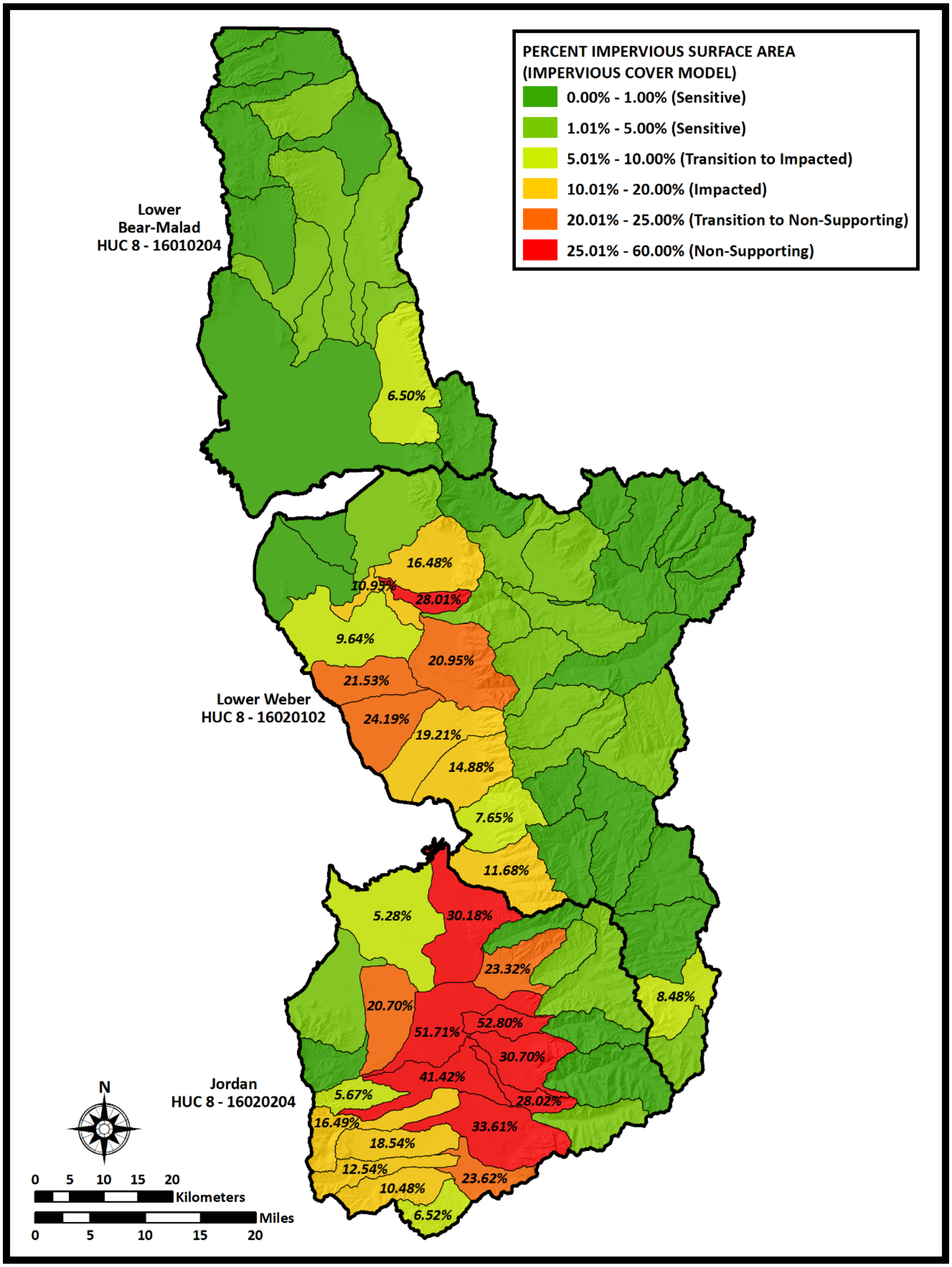

Figure 4-27. Impervious Cover Model (ICM) estimates for sub-watersheds within the study area (Schueler, 1994; Schueler et al., 2009). Sub-watersheds with greater than 5 percent impervious cover are labeled. Data source: USGS National Map Hydrography Viewer.

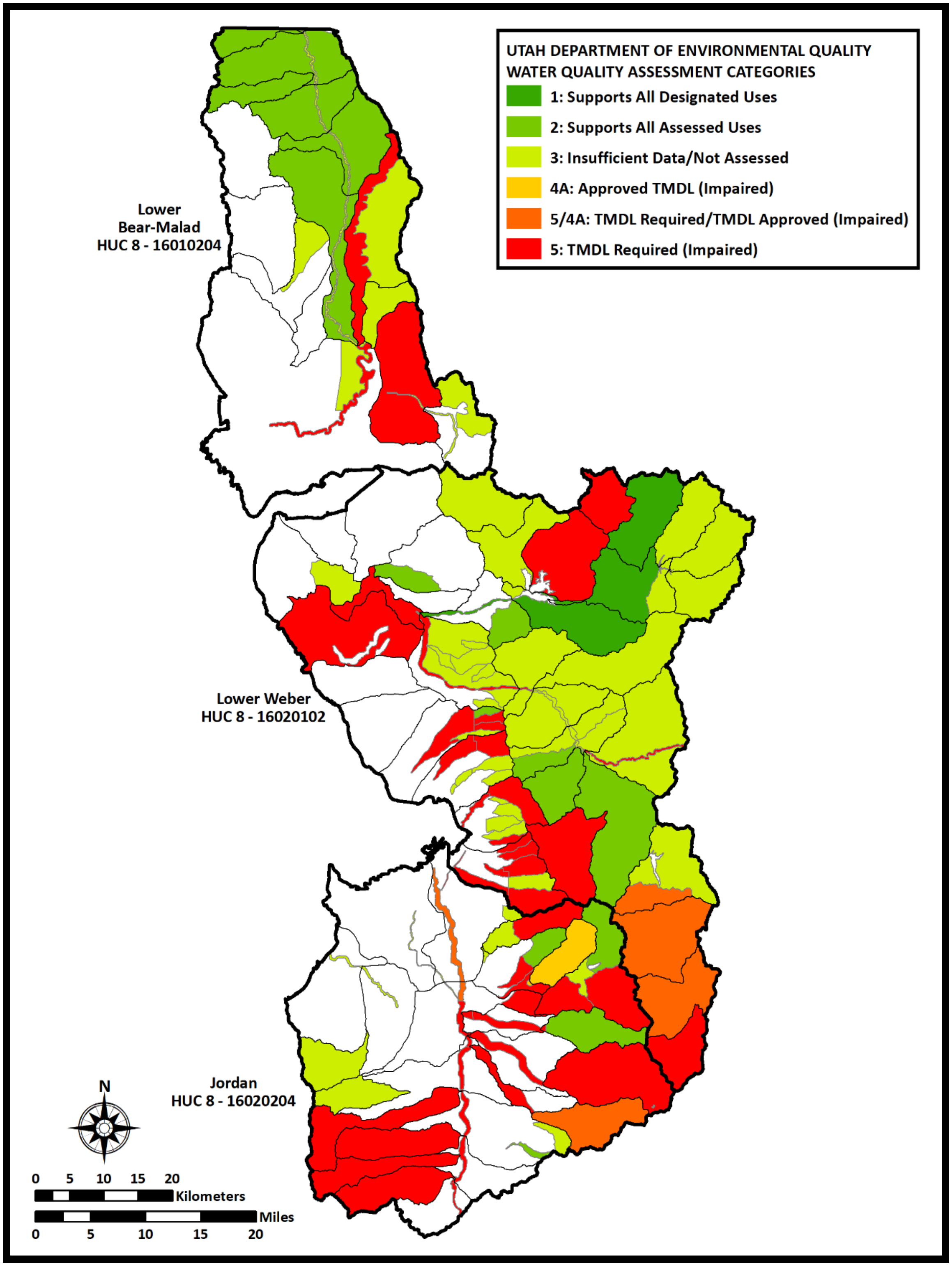

Figure 4-28. Utah Department of Environmental Quality water quality assessments for units within Lower Bear-Malad, Lower Weber, and Jordan sub-basins. Data source: Utah Environmental Interactive Map (https://enviro.deq.utah.gov/).

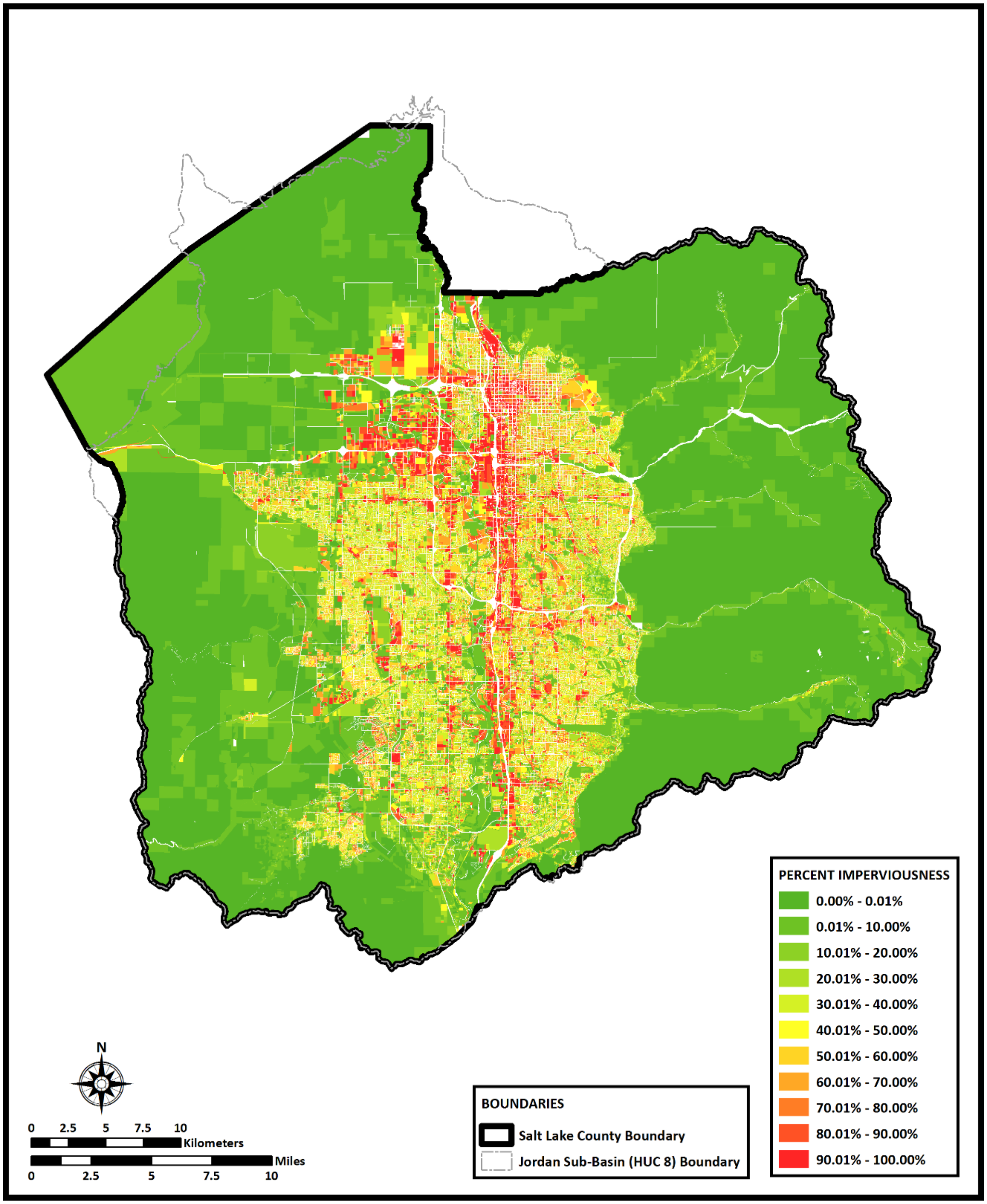

Figure 4-29. Parcel-based impervious cover for parcels within Salt Lake County. Data sources: Utah AGRC and USGS National Map Hydrography Viewer.

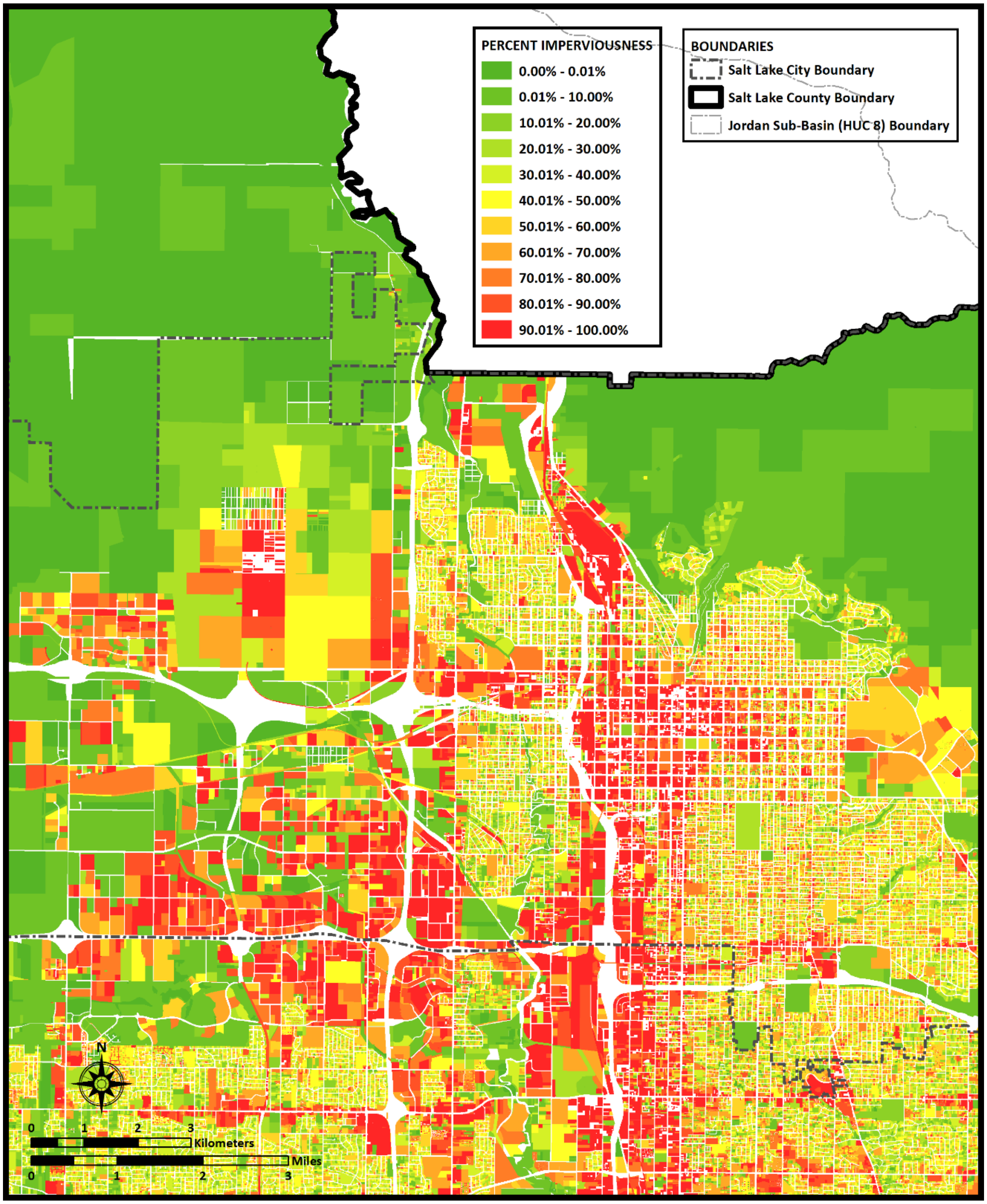

Figure 4-30. Parcel-based impervious cover for parcels within Salt Lake City and surrounding area. Data sources: Utah AGRC and USGS National Map Hydrography Viewer.

CHAPTER 5

CONCLUSION

Integrated planning and management approaches are purposeful holistic strategies that integrate ecological, biological, cultural, social, economic, and institutional factors into comprehensive analysis and action for the purpose of sustaining and enhancing the quality of natural and built environments (Munang et al., 2011). The central goal of integrated approaches is to balance the sustainability of natural resources and the integrity of ecosystem processes with human development and activities (Bellamy and Johnson, 2000). Integrated approaches to planning and management are being advocated by planners, watershed managers, foresters, ecologists, and public policy analysts to address the host of interconnected issues that span multiple jurisdictions and boundaries. Issues associated with remarkable rates of human population and urban development, such as nonpoint source pollution, urban sprawl, habitat loss, and resource deterioration, involve large numbers of decision-makers at different administrative and sectoral levels. Integrated approaches provide flexible frameworks and pragmatic solutions for addressing these issues (Margerum, 1997).

Integrated approaches to planning and management, such as bioregional planning and integrated water resources management (IWRM), have several defining characteristics. These approaches embrace the management of resources from broad and long-term perspectives to ensure that ecosystem processes and biotic communities remain viable (Pahl-Wostl, 2007). Large geographic areas that are defined by natural features, including watersheds, bioregions, or ecoregions, are emphasized to account for the broad spectrum of complex interconnections (Carlson and Stelfox, 2009). Interdisciplinary, flexible, and goal-oriented frameworks are employed to provide for successful planning and management solutions that can be tailored to suit individual ecosystem and societal resource use requirements (Munang et al., 2011). Collaboration, stakeholder involvement, and interjurisdictional coordination are implemented to foster shared understanding, to successfully balance the widest range of short-term and long-term goals, and to develop proactive and practical solutions (Carlson and Stelfox, 2009; Margerum, 1997).

Integrated approaches are finding increasing applications in community planning and natural resource management due to the long-term ecological and quality of life benefits. However, to successfully implement these approaches, several challenges must be overcome. The primary challenge of implementing integrated planning and management approaches is associated with the disconnect between existing political boundaries and naturally-defined regions. This disconnect can pose legislative problems and inhibit cooperative management due to differing county and municipal objectives and regulations (Cohen and Davidson, 2011). This issue can be addressed by embedding integrated approaches into comprehensive statewide and/or regional plans and programs that have unifying objectives. Within these comprehensive plans, appropriate spatial boundaries and scopes should be defined for successful implementation, and strategic frameworks that provide for interagency coordination should be outlined. Support for these comprehensive plans can be improved by establishing networks and community groups across multiple geographic scales for the purpose of organizing activities that build social capital and increase civic engagement (Bach et al., 2011).

The second major challenge of implementing integrated planning and management approaches is associated with decentralization and stakeholder involvement. With these elements, a diverse range of perspectives, interests, and opinions are introduced into decision-making, which can frequently delay the planning process and impede consensus building (Cohen and Davidson, 2011). Therefore, integrated planning and management frameworks should support innovative and flexible strategies for engaging a wide range of relevant stakeholders and for facilitating conflict resolution because public participation is a fundamental component of well-received plans and activities (Graf et al., 1999). Additionally, these frameworks should employ both bottom-up and top-down approaches to ensure that institutional arrangements provide for inter-sectoral linkages and to ensure that local community needs are carefully balanced with those of society as a whole (Bach et al. 2011).

Despite implementation challenges, there continues to be a pressing need for integrated planning and management, particularly in arid regions where water scarcity is problematic. The state of Utah, as one of the driest states in the nation, is undeniably no exception. Since colonization, limited quantities of water in the arid Intermountain West demanded inventive engineering solutions to sustain populations and to support agricultural practices. Consequently, water development and reclamation projects became defining features on the landscape and indefinitely changed the hydrology of the Intermountain West and Colorado River Basin.

Massive water development projects spanned decades without due consideration to environmental or hydrological impacts.

An increase in environmental awareness, a demand for more balanced solutions, growing water shortages and disputes, and rapidly increasing populations eventually yielded some legislative and management changes in Utah. State agencies began supporting statewide water planning efforts, implementing federal and state water quality policies and regulations, and instituting coordinated conservation measures to protect and restore wetlands and aquatic habitats. These management activities have gradually evolved into programs and plans that are more aligned with integrated planning and management approaches.

Utah's Watershed Approach for managing and reducing nonpoint source pollution was established in 1994 to guide the Utah Nonpoint Source (NPS) Management Program and to improve the quality of surface and ground water resources. Utah's Watershed Approach supports integrated planning and management through the holistic management of hydrologically-defined units, through extensive stakeholder involvement and interagency coordination, and through the development of responsive and long-term solutions to water quality problems (UDEQ, 2001). Utah's Wetlands Program, established in 2004, has supported extensive research and provided for the development of an assessment framework to improve wetland-specific water quality management decisions (UDEQ, 2014). Utah's Wetland Program Plan (WPP), initially published in 2010, was drafted to support integrated wetland conservation, management, and restoration and has formed the foundation for an integrated watershed-based approach to wetland management in Utah (Hooker and Jones, 2013).

Integrated approaches and strategies employed by Utah agencies have promoted the improvement of water quality and watershed condition; however, integrated planning and management remains controversial due to divergent political, social, and economic perspectives and interests. For integrated approaches to progress and evolve in Utah, obstacles will need to be addressed, policies and regulations may need to be reevaluated, and innovative and flexible frameworks will need to be developed to enhance planning and management processes, to increase public acceptance, and to improve the success of implementation.

While the resolution of these issues will require input from administrators, legislators, state agencies, and stakeholders, certain tools can be use in the interim to assist planning and management efforts and to encourage policy-makers to reach more informed decisions. The use of geospatial tools, including geographic information systems (GIS) and remote sensing, can support and improve a wide range of planning and management practices. Geospatial tools can support decision-making efforts, they can alleviate some of the complexity associated with evaluating multiple datasets, and they can promote an improved understanding of physical processes and change (Dai et al., 2001; Williams, 1999). The science and technology of remote sensing has enabled planners and managers to develop accurate and spatially explicit land use and land cover (LULC) information. In urban environments, LULC information, specifically information about the extent and amount of impervious surfaces, can provide an improved understanding of urban growth patterns and processes, can support sustainable urban planning, can contribute to the assessment of hydrological impacts, and can be used to develop implementation strategies that improve watershed health, wetland condition, and stormwater management.

Through a grant from the United States Environmental Protection Agency (USEPA) Wetland Program Development Grant Program, a high-resolution LULC dataset was developed for three watershed sub-basins in northern Utah for the purpose of supporting integrated water resources planning and management. A high-resolution LULC datasets can provide more detailed and accurate information, it can enhance understanding of complex and dynamic environments, and it can support improved planning, management, on-the-ground restoration, and conservation practices. The development of a high-resolution LULC dataset, with an emphasis on mapping and quantifying impervious surfaces, for three sub-basins in northern Utah was identified as a means to support Utah's WPP and Utah's Watershed Approach to managing nonpoint source pollution and to provide general assessments of the watershed condition in northern Utah. Specifically, this dataset can provide an indicator of cumulative stress from urbanization; it can support the development of ecologically relevant metrics that can be integrated into watershed health and wetland condition assessments; it can provide general assessments of watershed condition; and it can support the identification of sites in need of restoration and protection.

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