Drought Risk and Vulnerability Assessment and GIS Mapping Project

Prepared for

Commission on Water Resource Management
Department of Land and Natural Resources
State of Hawaii

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PREFACE

The purpose of this project is to supplement Hawaii's State Drought Plan by assessing drought risk statewide in terms of three drought impact sectors: the agriculture sector, the water supply sector, and the environment, public health and safety sector. As part of this study, data was collected, created, and analyzed within a geographic information system (GIS) to produce risk and vulnerability maps for the three impact sectors. Maps produced in this project will serve to guide and shape specific drought mitigation strategies.

Funding for this report was provided through the Pre-Disaster Mitigation (PDM) Grant Program's Planning Grant. This project was completed with the cooperation of the Federal Emergency Management Agency (FEMA), Hawaii State Civil Defense (HSCD), the State of Hawaii's Commission on Water Resource Management (CWRM), and State and County agencies that provided valuable GIS data, as well as other information that was critical to the completion of this report.

County Agencies Include:
Kauai County Planning Department
Kauai County Planning Department of Water
City and County of Honolulu's Planning and Permitting GIS Department
City and County of Honolulu's Board of Water Supply
Maui County Planning Department
Maui County Real Property Office
Maui County Water Department
Hawaii County Planning Department
Hawaii County Information Systems Department
Hawaii County Water Department

State Agencies Include:
The Department of Business, Economic Development and Tourism's GIS Program
The Department of Land and Natural Resources' Division of Forestry and Wildlife, Fire Management Program
Water Resources Committee of the Hawaii Drought Council

Federal Agencies Include:
National Climatic Data Center
National Drought Mitigation Center

ABSTRACT

Droughts are part of nature's climate variability; they have been prevalent in the past and will continue to occur throughout the State of Hawaii. Projections for groundwater demand on Oahu, given burgeoning populations and finite water supply that should be fully committed in 20 to 25 years, illustrate the potential for significant drought impacts. As the islands' water supply is limited, assessing drought risk is an important step in disaster mitigation planning. In this project, three impact sectors were identified as "at risk" to drought: the public water supply sector; the agriculture and commerce sector; and the environment, public health and safety sector. In this study, drought risk is defined as a combined product of drought frequency and vulnerability.

This project was designed to assess drought risk in Hawaii through the completion of a drought frequency analysis, the completion of a drought vulnerability analysis, and the integration of the results of both the frequency and vulnerability analyses into a statewide drought risk assessment. The drought frequency analysis for four counties was based on the Standardized Precipitation Index method. The analysis is presented for three drought stages (moderate, severe, and extreme) and for different drought durations (e.g., 3-month, 12-month). The results were combined with the statewide sector-based vulnerability analysis to identify drought risk areas for each county. A common risk area across all three sectors and three drought stages in the County of Hawaii is found on the western side of the island near Kona. For Maui County, the common risk area to the water supply and environmental sectors is within the Kula region. For the City and County of Honolulu, central Oahu appears to be the common risk area across all the sectors for two stages. For Kauai County, a small belt in the southeastern corner appears to be more vulnerable to some sectors and drought levels. Limitations of drought risk assessment and recommendations for future studies are given.

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1. INTRODUCTION

1.1 PURPOSE AND OBJECTIVE

The State of Hawaii is seriously affected by drought approximately every 2 ½ years with significant agricultural losses, water shortages, and wildland fires. In support of the forthcoming State Hazard Mitigation Plan, the Commission on Water Resource Management (CWRM), in cooperation with the Hawaii Drought Council (HDC), sought the development of a Statewide Drought Risk and Vulnerability Assessment. This statewide assessment utilized Geographic Information System (GIS) mapping techniques to identify areas at risk of meteorological, hydrologic, and agricultural drought, as well as environmental and socioeconomic impacts that may occur due to drought conditions.

GIS is a powerful and effective tool for developing integrated information from geographic features and environmental and social data attributes. Drought impacts can be devastating to the State of Hawaii's economy, the health and well-being of the human populace, and the environment. Thus, hazard mitigation planning that includes the delineation of drought risk areas through the analysis of interrelated parameters is essential to ensuring aspects of public safety, protecting against adverse drought related agricultural impacts, and safeguarding property. Such an assessment of drought risk areas is consistent with drought preparedness recommendations from the National Drought Mitigation Center (NDMC), and is also supportive of priority implementation actions identified in the Hawaii Drought Plan (HDP).

The HDP specifically recommended a geographic and sector-based risk assessment and vulnerability analysis for the State of Hawaii. This project was designed to incorporate the efforts of the HDC and its drought task forces, which are comprised of partnerships between government and non-governmental agencies as well as interests from the private sector. At the inception of the project, it was anticipated that a comprehensive drought risk and vulnerability assessment would be accomplished in several phases. This report contains the results of the initial phase of the project, including maps of at-risk areas and recommendations for both mitigation actions and future studies.

1.2 PROJECT DESCRIPTION

According to the NDMC, the incidence of drought can be described from several disciplinary perspectives, for example, meteorological drought, agricultural drought, hydrologic drought, and socioeconomic drought. Additionally, the resultant impacts of these different types of drought can be described and categorized in terms of economic, social, and environmental impacts sectors.

The primary working assumption for this drought risk and vulnerability assessment asserts that drought **risk** is a product of both the **frequency** and **severity** of drought and the corresponding **vulnerability**. This definition of drought risk is provided by the Western Drought Mitigation Council in their 1998 document titled *How to Reduce Drought Risk*. For the sake of clarification, this definition is not intended to imply that drought risk can simply be calculated through strict mathematical formulae. Notwithstanding, this definition effectively conveys the idea that risk is the result of the complex interplay of numerous variables; this concept is fundamental to the project design.

Frequency and **severity** are familiar concepts. In this case, **frequency** refers to the intermittence of drought occurrences and the rate of the recurrence. **Severity** refers to the geographic and temporal extent of the drought and the relative degree of abnormally dry weather experienced. In contrast, **vulnerability** to drought is conceptualized as the product of various human induced conditions; **vulnerability** is a function of land use patterns, population distribution, governmental policies, etc.

This project synthesizes these three concepts of drought frequency, drought severity, and drought vulnerability through the application of a GIS-based analysis. The resultant drought risk assessment is essentially the composite projection of areas at varying risk to economic, social, or environmental drought impacts, as determined through the overlay and analysis of multiple variables describing the occurrence of meteorological drought, agricultural drought, hydrological drought, and socioeconomic drought. The drought risk assessment was accomplished in three steps as follows:

- **Drought Frequency Analysis –** Compile and analyze meteorological data to determine drought frequency and severity statewide;
- **Drought Vulnerability Analysis –** Compile and analyze physical, environmental, and social features to determine drought vulnerability statewide; and
- **Drought Risk Assessment –** Integrate the results of the drought frequency analysis and the drought vulnerability analysis to arrive at a meaningful, statewide assessment of relative drought risk.

Drought Frequency Analysis: While there is a fair amount of GIS data available from numerous sources regarding hydrologic conditions, infrastructure, land uses, and physical features, there is a lack of data for meteorological conditions. Such meteorological data is essential to quantifying drought frequency and severity. Therefore, an important component of the initial phase of this project is the development of a drought frequency analysis with respect to geographic regions and the mapping of these results in GIS.

Drought Vulnerability Analysis: The drought vulnerability analysis was accomplished through the examination of three categories of drought impacts, or drought impact sectors. Data layers pertinent to the Agriculture and Commerce Sector, the Environment, Public Health and Safety Sector, and the Water Supply Sector were inventoried, combined, and refined to determine areas within each sector that are vulnerable to drought. In some cases, it was necessary to create GIS data layers from paper files or other data formats furnished by county agencies. This analysis produced GIS maps describing areas vulnerable to drought within each of the three sectors.

Drought Risk Assessment: Formulating this assessment of drought risk through the integration of the drought frequency analysis and the drought vulnerability analysis was challenging, as the assessment was dependent upon the successful development and application of numerous working assumptions for each of the three impact sectors. These working assumptions are critical to understanding the applicability of project recommendations. The working assumptions establish project limitations and acknowledge the need for updated data, additional data, and ground-truthing exercises. Within the guidelines provided by the working assumptions, the risk assessment combined the GIS maps of drought frequency and vulnerability to identify areas where the occurrence of drought coincides with the occurrence of vulnerability characteristics. The results of the risk assessment dictated the recommendations for mitigation activities and future follow-up studies discussed in section six of this report.

1.3 DROUGHT RISK AND VULNERABILITY MAPS

This project resulted in the development of drought risk maps for each of the four counties in the State of Hawaii (See Chapter 5). These maps delineate geographic areas that are "at risk" to drought conditions. Affected areas vary between the three impact sectors examined in this assessment, and it is anticipated that these maps will assist County, State, and Federal agencies in focusing and refining future drought mitigation and planning activities.

In addition to the paper version of the maps included in this report, electronic copies are also available and can be acquired by contacting the State Department of Land and Natural Resources, Commission on Water Resource Management.

2. BACKGROUND

2.1 STATE HAZARD MITIGATION PLAN

The Federal Disaster Management Act of 2000 required each state and territory to conduct hazard mitigation planning and to implement projects to reduce hazard impacts prior to a disaster occurrence. In the past, funding for hazard mitigation had typically only been available following a disaster declaration, based on a percentage of the estimated damages. The new laws have funded an overall planning effort independent of any specific hazard event to shape hazard mitigation. However, future funding for public assistance subsequent to disasters will be largely contingent on plan completion.

The Hawaii State Hazard Mitigation Forum, composed of County, State, Federal, and Private representatives for hazard mitigation planning purposes, has determined that the Hawaii State Hazard Mitigation Plan should be a ***Multi-Hazard*** plan. For the purposes of the plan, the term "multi-hazard" shall not be limited to discrete natural hazards, but include anthropogenic activities that could exacerbate hazard event impacts and potentially threaten the life and safety of the citizens of the State of Hawaii. The goal of the plan is to mitigate the impact of such potential disasters.

Although the State Hazard Mitigation Plan will encompass the broadest possible scope of disaster occurrences, the specific efforts are categorized by hazard area, and focus on nine natural hazards: hurricanes, tsunami, earthquakes, floods, volcanic eruptions and lava flow, coastal erosion, landslides, wildfires, and drought. For each of these specific categories of disasters, additional mitigation plans or strategies targeted at these disasters will be appended to the Hawaii State Hazard Mitigation Plan. Several of these hazard categories have current advisory boards and task forces that will be developing recommendations and strategies.

The Hawaii Drought Plan and the Drought Risk and Vulnerability Assessment Report will be referenced in the State Hazard Mitigation Plan. These additional studies are included to illustrate the spatial extent and severity of the drought and wildfire risk and vulnerability. These studies will assist in determining the degree to which these hazards present a problem for Hawaii and for its residents. It will also serve to recommend strategies to reduce and minimize the impact from drought and wildfires. The State Hazard Mitigation Plan must ultimately both highlight gaps in analysis and data to better understand our hazard risks, and propose or recommend specific projects that address short-comings or reduce risks in both short- and long-term timeframes. This report seeks to address these driving factors.

Specifically, this report will assist in identifying the risk and vulnerabilities related to drought. It will also enable staff and decision makers to develop projects and programs to minimize these risks. Although this report cannot be comprehensive with regards to drought, it does serve to advance our understanding of the intensity of the problem and help to suggest at least short-term solutions in reducing the impacts of drought in Hawaii.

2.2 HAWAII DROUGHT PLAN

2.2.1 PURPOSE AND SCOPE

The purpose of the Hawaii Drought Plan, Phase 1 is to define lines of coordination in the event of a drought, and to establish a framework and guide for federal, state, county, and private sector groups who have the capability and resources to develop effective preparedness and mitigation measures within their area of jurisdiction during a time of drought.

The drought plan discusses an early detection system that would include a comprehensive rainfall and climate monitoring system. The plan recommends that a network of people and/or organizations be identified that have the capability to assess and potentially minimize drought impacts. Also included are policies that can be implemented in an immediate time-frame in response to drought conditions. The plan describes the needed components of a successful drought plan, which includes historical occurrences of drought in Hawaii, drought frequency analysis, risk and vulnerability assessments, as well as potential impacts related to geographical location.

The most important component of the plan is the identification of the pre- and post-drought mitigation measures and education/outreach programs to be implemented by public and private agencies/organizations and the general public.

2.2.2 GOALS AND OBJECTIVES

There are four main concurrent goals of the drought plan. First, the drought plan should provide a timely prediction and monitoring system to set into motion prescribed actions to be taken during pre and post drought conditions. Second, the plan should conduct a risk assessment of key impact sectors including agriculture, water supply, the environment, and the urban/wildland interface. Third, the risk assessment should guide clear and concise mitigation measures to be undertaken during drought and non-drought periods. Finally, the plan should address the implementation of policies to provide and disseminate timely information to the public and the affected agencies.

2.2.3 DROUGHT IMPACT SECTORS

The Hawaii Drought Plan describes three drought impact sectors that are critical to the health and welfare of Hawaii’s people in terms of social, economic and environmental aspects. These impact sectors include: The Water Supply Sector, the Agriculture and Commerce Sector, and the Environment, Public Health and Safety Sector. The plan established a task force that is responsible for assessing vulnerability, mitigating against possible impacts, and/or responding to drought conditions impacting each of these sectors. These sectors are not mutually exclusive and as such, impacts in one sector may impact the other sectors.

The Water Supply Sector encompasses both public/private urban and rural drinking water systems, agriculture water systems, and other water networks. Because fresh water is crucial to human survival in a variety of direct and indirect ways, minimizing the impact of drought to Hawaii’s drinking water supply and other fresh water supplies is very important.

During drought periods, the agriculture and commerce sector experiences severe negative impacts due to dependence on both surface water and rainfall. Rainfall shortage-induced impacts are often exacerbated by the limits placed on ground-water pumping during drought periods. A persistent rainfall shortage and resultant lack of soil moisture can result in reduced ground cover and agricultural crop yields. Reduced ground cover can result in the reduction of livestock herd sizes and are also associated with increased incidence of erosion.

The Environment, Public Health, and Safety Sector in this project is primarily focused on wildfire incidence. Drought conditions heighten the potential incidence and spread of wildfire. Wildland fires not only endanger human lives at the urban/wildland interfaces, but also endanger species of flora and fauna which may already be especially susceptible due to drought conditions.

2.2.4 THE STAGES OF DROUGHT

The Hawaii Drought Plan utilizes a drought stage categorization formulized by T.B. McKee, N.J. Doesken, and J. Kleist in 1993 while developing the Standardized Precipitation Index (SPI). There are 3 stages of drought and a “Near Normal” period that are considered within the Hawaii Drought Plan. The 3 stages are: Stage One (Moderately Dry), Stage Two (Severely Dry), and Stage Three (Extremely Dry). According to the SPI Values associated with these categories, Hawaii is in near normal periods 68.2 percent of the time with a SPI range of 0.99 to -0.99 (Table 2.1).

Table 2.1 Drought Stages Based on SPI Values

Drought Stage	SPI Values	Time
Near Normal	0.99 to -0.99	68.2 %
Stage One (Moderately Dry)	-1.0 to -1.49	9.2 %
Stage Two (Severely Dry)	-1.5 to -1.99	4.4 %
Stage Three (Extremely Dry)	-2.00 or less	2.3 %

Source: Hawaii Drought Plan, Phase One

These stages differ in terms of the implications for the three impact sectors and according to the applicable time scale for the frequency analysis by sector (3 or 12 months). In the case of the Water Supply Sector, the drought stages are based on a 12 Month SPI (Table 2.2), and includes an examination of groundwater levels. The immediacy of negative drought impacts in the Agriculture and Commerce Sector requires using a 3 month SPI for the drought stages, as well as surface water level and reservoir storage level data (Table 2.3).

Table 2.2 Drought Characteristics for the Water Supply Sector

Drought Stage	General Characteristics
Normal	1. 12 Month SPI .99 to -.99 2. Groundwater levels are at normal
Stage One	1. 12 Month SPI -1.0 to -1.49 for two consecutive months 2. Water supply departments should declare "Low Groundwater Conditions-Cautions" if applicable
Stage Two	1. 12 Month SPI -1.5 to -1.99 for two consecutive months 2. Water supply departments should declare "Low Groundwater Conditions-Alert" if applicable
Stage Three	1. 12 Month SPI less than -2.0 for two consecutive months 2. Water supply departments should declare "Low Groundwater Conditions-Critical" if applicable

Source: Hawaii Drought Plan, Phase One

Table 2.3 Drought Characteristics for the Agriculture and Commerce Sector

Drought Stage	General Characteristics
Normal	1. 3 Month SPI .99 to -.99 2. Surface water levels and flows are at normal 3. Reservoir storage levels are above 75% capacity
Stage One	1. 3 Month SPI -1.0 to -1.49 for two consecutive months 2. 30 day surface water low flow value ≤ 10 year, but ≥ 20 year recurrence interval 3. Reservoir storage below 75% capacity
Stage Two	1. 3 Month SPI -1.5 to -1.99 for two consecutive months 2. 30 day surface water flow value ≤ 20 year, but ≥ 50 year recurrence interval 3. Reservoir storage below 50% capacity
Stage Three	1. 3 Month SPI less than -2.0 for two consecutive months 2. 30 day surface water supply low flow value ≤ 50 year recurrence interval 3. Reservoir storage below 25% capacity

Source: Hawaii Drought Plan, Phase One

Also referencing the 3 month SPI, is the Environment, Public Health and Safety Sector because of the urgency within this sector to mitigate against drought effects that will immediately impact human life. This sector also uses factors such as fire danger ratings, fire weather indices, fuel loading, and soil moisture content to determine the drought stage (Table 2.4).

Table 2.4 Drought Characteristics for the Environment, Public Health and Safety Sector

Drought Stage	General Characteristics
Normal	1. 3 Month SPI .99 to -.99 2. Normal surface water flows
Stage One	1. 3 Month SPI -1.0 to -1.49 for two consecutive months 2. Fire Danger Rating Scale
Stage Two	1. 3 Month SPI -1.5 to -1.99 for two consecutive months 2. Fire Danger Rating Scale 3. Issuance of No-burn warnings 4. Transport of municipal to rural water catchment areas
Stage Three	1. 3 Month SPI less than -2.0 for two consecutive months 2. Fire Danger Rating 3. Declaration of park and trail closure

Source: Hawaii Drought Plan, Phase One

2.2.5 HAWAII DROUGHT PLAN LEADERSHIP STRUCTURE

The Hawaii Drought Plan, Phase 1 was published in 2000 with numerous inputs from the Bureau of Reclamation, local entities, affected stakeholders, and private citizens. This Plan was prepared for use by the Hawaii Drought Council (HDC) to better coordinate management strategies for Hawaii in case of drought across impact sectors and jurisdictions. It also serves as a blueprint for structured actions to be taken. Evolved from an ad hoc working group during the 1998-1999 drought, the HDC is the steering group that oversees the implementation of drought related activities. Subsequently, a position of State Drought Coordinator was created and approved by the State Legislature.

Co-chaired by the directors of the State Department of Land and Natural Resources and the Department of Agriculture, the HDC consists of representatives from the State Department of Defense, the Governor's Office, and four County officials. Ex-Officio members include representatives from the Hawaii Association of Conservation Districts, Hawaii Farm Bureau, Hawaii Cattlemen's Council, and private water purveyors.

Serving as advisor to the HDC is the Water Resources Committee, which is responsible for monitoring rainfall, reservoir storage, ground water, and climate forecasts. A key function of this committee is to evaluate the current status of drought, and where possible, the future outlook of rainfall conditions. The Water Resources Committee is co-chaired by the State Commission of Water Resources Management and the Honolulu Board of Water Supply. Members of this committee include representatives from the National Weather Service, the State Civil Defense, the State Climatologist, the U.S. Geological Survey, the County Water Departments, and the Hawaii Agricultural Statistic Service.

Also key to the structure of the HDC are three specific task force groups representing sectors potentially impacted by drought: the Water Supply Sector, Agriculture and Commerce Sector, and the Environment, Public Health and Safety Sector. In contrast to the Water Resources Committee, the task force groups are concerned with the impact of impending or on-going drought upon the State's economy, environment, and natural resources such as forests. Many agencies, private purveyors, and stakeholders such as the Department of Land and Natural Resources, Department of Agriculture, Department of Health, State and County Civil Defense Agencies, the State Fire Council, County Fire Departments, farmers, ranchers, landowners, Hawaii Association of Conservation Districts, and others participate in these task force groups.

Essential to the HDC structure are the County/Local committees. They are responsible for identifying local areas of high risk and developing methods to mitigate the effects of drought.

2.3 UNDERSTANDING DROUGHT AND DROUGHT RISK

2.3.1 DEFINING DROUGHT

Definitions of drought can be categorized into two types: conceptual or operational. Conceptual definitions are general and help people understand the concept of drought. Operational definitions help identify the duration and severity of drought, and are more useful in recognizing and planning for drought. Three operational definitions of drought are presented below.

Meteorological drought is region specific due to the regional nature of atmospheric events. It is defined as to the degree of dryness and episode duration in variance with normal conditions. Assessing the extent of metrological drought requires data sets such as daily rainfall information, temperature, humidity, wind velocity and pressure, and evaporation.

Agricultural droughts are identified by linking the characteristics of meteorological drought (rainfall shortages) to agricultural impacts. Accounting for the susceptibility of crops during different stages of development would further require data sets on soil texture, fertility and soil moisture, crop type and area, crop water requirements, pests and climate.

Hydrological drought refers to surface and ground water supply deficiencies reflected in declining surface and ground water levels. Although it is a natural phenomenon, hydrological drought is often exacerbated by human activities and land use. To assess the degree of hydrological drought the following data sets would be required: surface water area and volume, surface runoff, stream flow measurements, infiltration, and ground water levels.

Finally, socioeconomic drought refers to the occurrence of adverse effects on supply and demand of economic goods brought on by the three other types of drought mentioned previously. The drought is characterized by the demand for a good exceeding the supply as a result of a shortfall in water supply. The data sets required to examine the effects or extents of a socioeconomic drought are figures on human and animal populations and growth rates, water and fodder requirements, severity of crop failure, and industry type and water requirements.

Droughts produce a complex set of impacts that in general, can be defined as direct and indirect. When referring to droughts, direct impacts include reduced cropland, rangeland, and forest productivity, increased fire hazard, reduced water levels, increased livestock and wildlife mortality rates, and damage to wildlife and fish habitat. The indirect impacts are characterized as the consequences of these direct impacts. Drought impacts can also be categorized by the sector which is impacted. These types of impacts are economic, environmental, or social. Many of the economic impacts occur in the agriculture and related sectors, because of their reliance of surface and ground water supplies. In addition to losses in yields to both crop and livestock production, impacts can be indicated by income loss to farmers, which has a ripple effect impacting income to retailers and others who supply goods and services to farmers. Environmental impacts refer to the losses incurred as a direct result of drought or indirectly such as wildfire damage to plant and animal species. Direct and indirect negative impacts can include degradation of wildlife habitat, air and water quality, landscape quality, loss of biodiversity, and soil erosion. Social impacts involve public safety, health, water use conflicts, quality of life issues, and socio-spatial inequities in the distribution of impacts and disaster relief. Many impacts that have economic and environmental effects also have social components as well.

2.3.2 PRINCIPLES OF DROUGHT RISK

How does one explain or define drought risk? According to a document produced by the Western Drought Coordination Council (WDCC) titled “How to Reduce Drought Risk,” drought risk is a function of one’s vulnerability to drought, the frequency of occurrence, and the severity of drought conditions (Knutsen, et. al., 1998). Working from the premise that risk assessment begins with evaluating vulnerability, the potential impacts across drought types will be discussed.

2.3.2.1 VULNERABILITY

Vulnerability is defined as the characteristics of populations, activities, and/or the environment that make the population susceptible to the effects of a drought. The degree to which one is vulnerable depends on the environmental and social characteristics of the region and is measured by the ability to anticipate, to deal with, resist, and recover from the drought. According to the WDCC report, a vulnerability assessment provides a framework for identifying or predicting the underlying causes of drought impacts. This framework aids in bridging the gap between identifying the impact severity and the policy development process by focusing on the causes of this vulnerability, rather than the actual impacts (Knutsen, et. al., 1998). For example, the actual impact may be observed in reduced crop yields or reduced livestock productivity. To begin to understand the vulnerability factor, one must first be able to identify the impacts that are caused by drought in your local area.

The common types of impacts caused by drought can be grouped into three categories: economic, environmental, and social. The range of economic impacts is broad with the more frequent impacts involving agriculture losses in crops and livestock, industrial losses in timber and fishery production, geographic specific decline in the tourism and recreation industry, and the decline in relevant food production. Commonly observed environmental impacts include damage to animal and plant species, soil erosion and depletion, loss to wetlands, increased incidence of wildland fires, and overall biodiversity losses. Social impacts also vary widely, the most pressing being health related problems including nutrition depletion, indirect increase in vector borne disease concentrations, and ultimately loss of human life. Another significant social impact with particular pertinence to Hawaii is burgeoning water rights conflicts.

The hierarchical ordering of impact priorities involves factors such as economic cost, extent of impacted areas, immediacy, public opinion, size of impacted populations, and the ability of the impacted areas to recover. Prioritization should not be taken as the definitive statement on impact significance, but instead as a framework to identify and guide future actions. It is important to note that although prioritization did not occur as part of this risk and vulnerability assessment, it is a worthwhile area for future studies.

After a priority list of impacts has been generated the bulk of the vulnerability assessment can be conducted. The main focus of the vulnerability assessment would be to identify the causes of the prioritized drought impacts, in the process bridging the gap between impact identification and the policy formulation phase of drought risk assessment. For the sake of this project the policy formulation phase would be the codification and enactment of mitigation strategies by relevant agencies. For example, a direct impact due to low precipitation, characteristic of a agricultural drought, is low yields in agriculture crops, but the vulnerability may be a product of the farmer’s/rancher’s respective decision to refrain from using drought resistant seeds or to not cull back livestock herds in the face of oncoming drought. So, for each impact, it is important to trace the web of decision-making in relation to real and perceived hazards.

Hawaii's study did not involve an impact analysis component, but conducting a drought impact analysis study has been discussed as a possible future endeavor.

2.3.2.2 FREQUENCY OF OCCURRENCE

Knowing that a particular sector is vulnerable to drought impacts is only one component of understanding the risk to drought. Determination of how often a drought event may occur is the other key component. Table 2.5 displays a ranking of drought episodes in Hawaii based on data gathered from the State rain gage network from 1933 to 1984. The table indicates that the State experienced a meteorological drought as often as every year to every nine years, with the longest drought duration being six months.

Table 2.5 The Ranking of Hawaii's Droughts

Event Rank	Drought Event From		To		Severity	Magnitude	Duration (Mo)
1	1977	Sept	1978	Feb	-16.22	-2.70	6
2	1975	May	1975	Oct	-14.85	-2.48	6
3	1953	July	1953	Nov	-14.29	-2.86	5
4	1933	Aug	1933	Nov	-11.61	-2.90	4
5	1976	Dec	1977	Feb	-8.97	-2.99	3
6	1943	Nov	1944	Jan	-8.47	-2.82	3
7	1983	Feb	1983	Apr	-8.33	-2.78	3
8	1984	Aug	1984	Oct	-7.63	-2.54	3
9	1941	Feb	1941	Apr	-7.54	-2.51	3
10	1973	Jun	1973	Aug	-7.45	-2.48	3
11	1945	Jan	1945	Feb	-5.80	-2.90	2
12	1949	Sept	1949	Oct	-5.57	-2.78	2
13	1962	Nov	1962	Dec	-5.19	-2.59	2
14	1971	July	1971	Aug	-4.99	-2.50	2
15	1973	Jan	1973	Feb	-4.42	-2.21	2
16	1949	Apr	1949	May	-4.32	-2.16	2
17	1952	Aug	1952	Sep	-4.10	-2.05	2
* These records are from a complete rain-gage network, February 1931 to December 1986							
1	1926	Jan	1926	May	-14.28	-2.86	5
2	1897	Jan	1897	May	-11.83	-2.37	5
3	1898	Nov	1899	Feb	-9.86	-2.47	4
4	1931	Jan	1931	Mar	-8.19	-2.73	3
5	1899	Nov	1900	Jan	-8.09	-2.7	3
6	1905	Jan	1905	Mar	-7.37	-2.46	3
7	1919	Feb	1919	Apr	-6.68	-2.23	3
8	1922	Jun	1922	Jul	-5.07	-2.54	2
9	1906	Feb	1906	Mar	-4.83	-2.41	2
10	1912	Aug	1912	Sep	-4.21	-2.11	2
** These records are from an incomplete rain-gage network (Min. 50% of Network),							

January 1895 to January 1931

Source: Giambelluca, et. al. 1991. Drought in Hawaii, Report R88. State of Hawaii, Department of Land and Natural Resources.

It is important to note that the report that produced this table did not consider drought events lasting for more than 12-months. Recent long-duration drought episodes require the examination and study of multi-year drought occurrences. The determination of drought severity and magnitude is based on an operational definition of drought that employs the examination and analysis of precipitation totals over a period of time. Hence, determining the rainfall deficit occurrence is also critical in predicting the onset of drought, the vulnerability, and ultimately, the drought risk.

2.3.2.3 SEVERITY OF DROUGHT CONDITIONS

The last phase of a risk analysis is an impact severity analysis. Although this study did not conduct a drought impact analysis for this phase of the project, it is an area recommended for future study. The rationale follows that, for example, the drought impact data in Table 2.5 can be given as a value in terms of severity and magnitude (larger negative values equates a greater impact), but these values do not provide a clear picture as to what was impacted, or to what degree impacts occurred. Such an impact severity analysis would allow for more informed mitigation efforts.

2.4 PREVIOUS DROUGHT RISK AND VULNERABILITY STUDIES

Although very few drought risk and vulnerability analyses have been completed, this study draws upon two of the established methodologies that have been summarized in the following section. Both studies take risk and vulnerability analysis to fruition in the form of policy recommendations, although the Antigua and Barbuda study was more complete in this regard. The implication is that both studies had much larger scopes as they were intended to be multi-phase endeavors. Hawaii's analysis is then a much more focused synthesis of their risk and vulnerability methodologies with an emphasis on GIS-based analysis, consistent with Northeast Thailand's study.

2.4.1 DROUGHT HAZARD ASSESSMENT AND MAPPING FOR ANTIGUA AND BARBUDA

2.4.1.1 BACKGROUND, VULNERABILITY, AND POLICY MEASURES

In April of 2001, a drought hazard assessment and mapping study was produced for Antigua and Barbuda, the largest of the British Leeward Islands as part of the Post-Georges Disaster Mitigation Project (PGDM). The major objective of this study was to formulate national goals, objectives and actions to reduce the vulnerability of Antigua and Barbuda to drought. This study was composed of several phases: assessment phase, impact and vulnerability determination phase, risk analysis phase, drought mapping phase, and the development of local indicators of drought.

To determine Antigua and Barbuda's vulnerability to drought, an extensive data collection and compilation phase was undertaken, which included an assessment of meteorological conditions, environmental conditions, land use and management conditions, and infrastructure conditions. The meteorological conditions included precipitation, temperature, wind, slope exposure, relative humidity, cloud cover, and evaporation and transpiration data. The environmental component included geology, slope, soil types, vegetation types and coverage, soil water deficiencies, and water resources. The land use and management data included crop information regarding type, quantities, and location of farming practices for crop and livestock, livestock population inventories, distribution and management practices, and market prices. The infrastructure assessment inputs for this study included gathering data on population settlements and communities, hotels and tourist zones, dams and storage reservoirs, desalinization and water treatment plants, waste water treatment facilities, irrigation and water distribution systems, water catchment systems, and overall water supply and demand figures.

During the impact and vulnerability phase of this study, a historical record of past years was compiled to examine the environmental impacts on watershed and habitat degradation, and the economic impacts on agriculture, tourism, and settlements. When considering drought severity and the associated impacts, the historical examination found that the drought that lasted from January of 1983 to August of 1984 was probably the worst drought on record to hit Antigua. The study found that drought impacts were more severe in watersheds where vegetation had shallow root systems associated with shallow soils levels; such impacts were due to soil moisture deficiencies. There were documented observations of increases in plant mortality in certain plant species. This resulted in a readily apparent increase in the browning of the landscape and a decrease in canopy cover in wooded areas. A ramification of the drought related soil exposure was soil erosion, compounded by the forces of wind and water when the rains finally came. It was determined that this soil loss and the related reduction in soil fertility, ultimately affected the composition and function of the ecosystem. In terms of habitat degradation, the study determined that before the drought, habitats were already susceptible due to overgrazing. Thus, habitats were doubly impacted in certain critical watersheds.

Economic impacts were felt in the production of food crops because most farms in Antigua/Barbuda were, and still are, dependent on precipitation to provide water to the food crops. As a result, widespread crop failure occurred during the drought. Even for farms that had access to potable water or irrigation systems, the drought meant a systemic rationing of supplies, with priority given to households and hotels. In terms of livestock, the drought affected the weight, health and productivity of the livestock, hence reducing marketability. Along with reduced fertility, animals suffered from dehydration due to the shortages in water. In total, the drought produced the following impacts in the livestock economy: setbacks in the development of herds, a reduction in herd weights and marketability, a greater dependence on imported meats, and finally significant income loss by farmers.

Despite being given priority during the water rationing, the visitor economy was also negatively impacted. The degraded landscape was aesthetically less appealing to visitors, hence reducing return visits and resulting in negative publicity. The hotels were impacted by the water shortage as visitor satisfaction was compromised by limiting water for hygienic purposes. In short, the drought impacted the tourist economy by shortening vacation times and resulting in cancellations by tourists, increasing water costs for hotels, and a generalized loss of income in the local tourist industry. Within residential communities, the drought conditions impacted overall household incomes, the sanitary and health conditions, and ultimately even school and work. Households that were impacted the greatest were those that relied on farming as the primary source of income.

To reduce future vulnerability in Antigua and Barbuda to drought within each of their respective impact sectors, several measures have been implemented or proposed. Within the agriculture sector, crop production was and still is heavily dependent on rainfall for watering crops. However, desalinization now accounts for 62% of the potable water. Although households and hotels are less vulnerable to drought through these means, it is important to note that there is widespread reluctance to use this source for irrigation due to the costs associated with water processing. As a means to develop other alternatives to reduce the vulnerability of crops, the study suggested that there be greater effort spent on matching crops to land capability. The study suggested the use of the Organization of American States (OAS) land capability maps by farmers to match crops to particular land types, to improve soil conservation through the use of mulch, institute water conservation practices, and to create a government sponsored drought relief program to assist farmers.

Within the livestock sector, overgrazing is the primary contributor to drought vulnerability. The study proposes a drastic reduction in goat populations, and rigid controls on where livestock are allowed to graze. To achieve these results, government programs in population control and forest restoration practices must be established. Planning recommendations included the establishment of policy controls for water and soil conservation, exploring the feasibility of subsidies to reduce water rates, developing adequate institutional infrastructure for drought planning, increasing support for drought related research, regulating livestock access to public lands, and stiffer penalties for livestock owners for damages incurred to crops and gardens.

As stated previously, the existence of desalinization plants have made most hotels less vulnerable to droughts, but given the uneven access to the technology and overall costs, the study asserts that rationing water by using water saving fixtures is a measure that should be implemented throughout the industry. Project findings clearly indicate inefficiencies that should be addressed, such as decreasing water waste by improving irrigation practices, creating a metered system for large properties, and renovating old plumbing systems. The study also encouraged the creation of an inventory system to track tourist facility and golf course compliance with newly formed policies, and to assess overall drought preparedness.

Much like the hotels, residential communities have become less vulnerable with access to desalinized water, but most communities are still impacted by rationing. Hence, the need to install water saving fixtures in new homes and the retrofitting of older homes is required. An overarching concern touched on in the study is the need to better manage land use and resource use practices to prevent groundwater aquifer contamination.

2.4.1.2 RISK ANALYSIS

For this study, risk is composed of two factors: the recurring environmental or metrological events that are beyond the control of man, and the human policy or land use practices that increase the vulnerability to the event. Based on these factors, criteria were established to rank the risk of drought on the scale listed below:

Low Drought Risk: <4
Moderate Drought Risk: 5-6
High Drought Risk: 7-8
Very High Drought Risk: >9

The drought risk criteria used in this study are listed in Table 2.6. The criteria include: Meteorological/Environmental Criteria, Hydrological/Infrastructure Criteria, and Human/Land Use Criteria. The assumptions regarding each of the criteria are also listed in Table 2.6. Under the meteorological/environmental criteria, areas are more vulnerable to drought if they receive less than 40 inches of rain annually, creating moisture stress, are excessively exposed to wind and marine fluctuations such as along the east coast of Antigua and Barbuda, have shallow soils with limited soil moisture retention, have slopes greater than 11 degrees and are thus more prone to erosion, and are categorized as having cactus or scrub vegetation.

The hydrological/infrastructure criteria was based on the assumptions that areas without wells have undue reliance on precipitation for water needs, although groundwater sources could potentially be tapped during extreme drought conditions, and that areas that do not have agricultural reservoirs have severely limited means to provide access to water for farmers during drought conditions.

With the Human/Land use category, grazing areas that have densities of greater than 6 goats or sheep per hectare or 1.5 cattle per hectare for pasture areas without irrigation are not sustainable during a drought event. Furthermore, areas with a population density greater than 5000 people per square mile are more vulnerable due to increased demand on localized resources, negatively impacted aquifer recharge, and inadequate space for household water storage during rationing periods. Finally, the vulnerability of agricultural lands located greater than 1 mile from water-main supply sources is based on reliance on precipitation and inherently complicated access to irrigation.

Table 2.6 Drought Risk Criteria for Antigua/Barbuda

Type	Rank
Meteorological/Environmental	
Rainfall < 40 inches	1
Exposure to wind and marine influences	1
Shallow soils	1
Slopes >11°	1
Cactus scrub vegetation	1
Hydrological/Infrastructure	
Absence of wells	1
Absence of agricultural reservoirs	1
Human/Land Use	
Grazing	1
Crop location	1
Population density > 5000 per sq. mile	1

Source: Drought Hazard Assessment and Mapping for Antigua and Barbuda

2.4.1.3 MAJOR ISSUES

The study determined that the following issues should be considered by policy makers and should shape both drought mitigation efforts for future research:

a. Overgrazing is regarded as the most critical factor contributing to drought vulnerability.
b. A nationwide network of meteorological stations is needed to improve all drought related analysis and inform decision making.
c. Existing vegetation data is inadequate, hence the need to classify and map vegetation zones. Such a classification system would improve management capacity. This classification system should also include a soil moisture index by various plant types.
d. Increased capacity in agricultural ponds and reservoirs is crucial to blunting the worst drought impacts across sectors.
e. Desalinization has decreased drought vulnerability in certain sectors relying on potable water, but it is far from a comprehensive solution. Desalinization only produces 62 percent of the potable water, and additional reliable water production is needed to further reduce the vulnerability.

2.4.2 AN EVALUATION OF DROUGHT RISK IN NORTHEAST THAILAND USING REMOTELY SENSED DATA AND GIS

2.4.2.1 BACKGROUND AND METHODOLOGY

This study was submitted as a paper and presented at the 21st Asian Conference on Remote Sensing in 2000. The objective of this study was to develop and model drought risk areas with a set of geographic based themes using remote sensed data and geographic information systems (GIS) in Northeast Thailand. Drought in Northeast Thailand has a profound effect on the way of life and the regional economy, impacting the regional food supply with relevant multiplier effects.

The underlying assumption in this study was that drought severity is a function of rainfall, hydrology, and the physical aspect of the landscape. In terms of water deficiency, this paper used the operational definition of drought (meteorological, hydrological, and physical drought) to establish the logic behind the GIS layer selection and analysis.

The meteorological drought component was performed using mean annual rainfall data over a 15 year period, with data collected from 264 rain gauge stations. These records were then converted into point data, and interpolated in GIS by a geostatistical kriging interpolation method, to establish a spatial mean across the entire surface (Houlding, 2000). Kriging depends on models of spatial autocorrelation, which can be formulated as a covariance or as variograms. In practice, the effectiveness of kriging depends upon an appropriate selection of the model variogram parameters, and if the available observations are representative of the entire area. A measure of the reliability of the interpolation, based on the estimation of kriging error variance, is of considerable interest given the use of geostatistics as an aid to mapping (Houlding, 2000). A threshold was then established using a decile range to determine a decile rainfall.

The hydrological drought component used an overlay process within the GIS environment to analyze surface water coverage, irrigation coverage, stream density, and groundwater yield and quality. Surface water sources and irrigated area GIS layers were developed from image analysis and classification of Landsat Thematic Mapper (TM) imagery that had been taken over a year long period, as well as ground truthing exercises. Stream density was calculated from stream lengths within subwatersheds. The groundwater yields and quality assurance datasets were readily available through the mineral resource department.

The physical drought component used land type or form, drainage condition, and land use as the variables within this portion of the analysis. Similar to the analysis performed in the hydrological component of the study, land form and land use data were created from the Landsat TM remote sensing data, and drainage condition were compiled from soil maps. The resulting data layers were combined to determine the drought risk areas. Table 2.7 describes the ranking scheme developed from the GIS layers involving meteorological, hydrological, and physical drought to determine a spatial drought severity index.

Table 2.7 Classification for Drought Severity Index

Variables	Class	Drought severity
Mean annual rainfall (Decile range)	0 - 1130.065 mm.	4
	> 1130.065 - 1276.133 mm	3
	> 1276.133 - 1431.076 mm.	2
	> 1431.076	1
Irrigated area and water source	Water source 0 - 0.5 km^2	
	Area beyond water source >0.5 km.	4
	Area beyond water source >0.12 - 0.5 km.	2
	Area beyond water source 0 - 0.12 km.	1
	Water source 0.5 - 5 km^2	
	Area beyond water source >1 km.	4
	Area beyond water source >0.25 – 1 km.	2
	Area beyond water source 0 - 0.25 km.	1
	Water source 5 –10 km^2	
	Area beyond water source >1.5 km.	4
	Area beyond water source >0.5 – 1.5 km.	2
	Area beyond water source 0 - 0.5 km.	1
	Water source > 10 km^2	
	Area beyond water source >3 km.	4
	Area beyond water source >1 - 3 km.	2
	Area beyond water source 0 - 1 km.	1
	Area within irrigated area	1
Groundwater yield and TDS.	3 m^2 / hr. & TDS. > 1500 mg/l	4
	2 - 10 m^2 / hr. & TDS. > 750 - 1500 mg/l	3
	10 –20 m^2 / hr. & TDS. <750 mg/l	2
	>20 m^2 / hr. & TDS. <750 mg/l	1
Stream density	0 – 120.98 m/ km^2	4
	120.99 – 248.17 m/ km^2	3
	248.18 – 406.89 m/ km^2	2
	>406.89 m/ km^2	1
Land form	Mountainous	4
	Dissected erosion surface	3.5
	High terrace	3
	Middle terrace	2.5
	Low Terrace	2
	Flood plain	1
Drainage condition	Excessively drained	4
	Well drained	3.5
	Moderately drained	3
	Somewhat poorly drained	2.5
	Poorly drained	2
	Very poorly drained	1
Land use	Field crop / Deciduous forest / Village	4
	Mixed field crop / Forest and mixed crop	3.5
	Grass land / Shrub / non-use	3
	Mixed paddy / Mixed ever green forest	2.5
	Tree / Fruit tree / Swamp and other	2
	Paddy / Mixed fruit tree / ever green forest	1.5
	Water source / Riparian / Swamp	1

Source: An Evaluation of Drought Risk Area in Northeast Thailand Using Remotely Sensed Data and GIS

2.4.2.2 RESULTS

The results of this study showed that based on the criteria of meteorological, hydrological, and physical drought, only 11.20% of the areas in the study area are at severe drought risk, while a majority of the study area (32.06%) would be under moderate drought risk based on the data used, and ranking scheme. Table 2.8 describes the results in further detail.

Table 2.8 Drought Risk

Drought class	Meteorological Drought (%)	Hydrological Drought (%)	Physical Drought (%)	Drought risk Area (%)
Very Mild	5.61	28.12	13.40	29.40
Mild	35.20	20.22	42.78	27.34
Moderate	34.03	38.07	38.61	32.06
Severe	25.16	13.59	5.21	11.20
Total	100.00	100.00	100.00	100.00

Source: An Evaluation of Drought Risk Area in Northeast Thailand Using Remotely Sensed Data and GIS

2.5 DROUGHT RISK AND VULNERABILITY IN HAWAII

According to the Hawaii Drought Plan (2000), after establishing the Hawaii Drought Council the next priority was to conduct a drought risk and vulnerability study within the subsequent 12-18 months. This study was initiated with funding from FEMA's Pre-Disaster Mitigation Grant Funds to the State of Hawaii Department of Defense, Civil Defense Division. In September 2002, the CWRM undertook the statewide drought risk and vulnerability analysis.

The proposed scope of work includes (1) GIS-based risk assessment of drought impact areas, (2) drought frequency analysis, and (3) an integration of these components to form a vulnerability analysis. The risk assessment involves both GIS data-gathering and data creation so as to compile asset layers and analytical layers for a visual presentation of risk. For the drought frequency analysis, historical rainfall records for Hawaii from the NOAA/National Climatic Data Center were obtained and a drought frequency analysis based on the Standardized Precipitation Index method was conducted. Digital mapping of the drought frequency for various drought stages is provided. For the integration phase of the project the drought frequency contours (in percentages) is overlaid with the GIS-based risk assessment to create a composite layer describing areas of varying drought risk for the State. For the sake of a more robust study, deficiencies in data, alternative methodologies for risk and vulnerability assessment, and recommendations for future actions shall be identified.

Precipitation is an important factor in examining drought risk due to its importance in water resources. In most tropical locations rainfall is highly variable from year to year and Hawaii is no exception. This variability is very evident in extreme rainfall values from several stations during the periods of record.[1] Over a 79-year period, downtown Hilo's highest annual total was 207 inches, with a low record of 72 inches. Honolulu, over a 62-year period, the extremes of high and low was 46 and 10 inches, respectively. In Mana, Kauai, over a 61-year period, the extremes were 48 and 5 inches. During a period of only 23 years, Kukui, Maui had extremes of 578 and 250 inches. With such wide variability in rainfall, it is inevitable that there are occasions of drought, and sometimes with severe economic losses.

Drought years tend to be the most extreme when winter rains fail to materialize, where only one or no winter rain storms of great magnitude occur. Among the winters of record, rainfall was below average throughout most of the State of Hawaii from 1925 to 1926. During this period, Honolulu experienced below average rainfall from November to April, and the total rainfall for the 5 month period from January to May was less than 3 inches. During this drought, for over 100 consecutive days rainfall did not exceed 0.3 inches per day, and often fell far short of this total. These daily rainfalls totals were insignificant in terms of appreciable benefit to crops. During this same period there were severe water shortages in many areas of Hawaii County, although some regions received significantly more rain than Honolulu.

Drought damage was observed as being the greatest on rangeland and in pineapple areas, where irrigation was not being practiced. According to Table 2.9, between 1998 and 2002, there has been an estimated loss of 15.5 million in cattle alone, with the majority of those losses occurring on the Island of Hawaii and Maui.

Based on the operational definition of meteorological drought, in 1991 a study was conducted in Hawaii examining rain gage network data across the State of Hawaii to examine

[1] Climate in Hawaii, http://www.wrcc.dri.edu/narratives/HAWAII.htm

historical drought events, their severity, magnitude and duration.[2] Table 2.10 to Table 2.15, illustrate the results. Examination of the results, shows that in the period analyzed for each respective island, in terms of severity and duration, Oahu had the most severe drought occurring over a 12 month period from November 1983 to October 1984 (Table 2.14). The severity value for this drought episode was a -31.48 (Based on the Bhalme and Mooley Drought Index-BMDI), severity is measured as a negative value). The other islands have also experienced lengthy (8 to 9 month periods) and severe (-26.07 to -21.06 BMDI severity scale values) droughts in the past.

[2] Giambelluca, T.W., et. al., 1991. Drought in Hawaii, Report R88. State of Hawaii, Department of Land and Natural Resources, Commission on Water Resource Management

Table 2.9 History of Drought in Hawaii

Year	Area	Remarks
1901	North Hawaii	Severe drought, destructive forest fires.
1905	Kona, Hawaii	Serious drought and forest fires.
1908	Hawaii and Maui	Serious drought.
1912	Kohala, Hawaii	Serious drought and severe sugarcane crop damage for two years.
1952	Kauai	Long, severe dry spell.
1953	Hawaii, Kauai, Maui and Oahu	Water rationing on Maui; Water tanks in Kona almost empty; 867 head of cattle died; Pineapple production on Molokai reduced by 30 percent; Rainfall in the islands had been 40 percent less than normal.
1962	Hawaii and Maui	State declared disaster for these islands; Crop damage, cattle deaths, and sever fire hazards; Losses totaled $200,000.
1965	Hawaii	State water emergency declared; Losses totaled $400,000.
1971	Hawaii and Maui	Irrigation and domestic water users sharply curtailed.
1975	Kauai and Oahu	Worst drought for sugar plantations in 15 years.
1977 – 1978	Hawaii and Maui	Declared State disaster for these islands.
1980-81	Hawaii and Maui	State declared disaster; Heavy agricultural and cattle losses; Damages totaling at least $1.4 million.
1983 – 1985	Hawaii	El Niño effect; State declared disaster; Crop production reduced by 80 percent in Waimea and Kamuela areas; $96,000 spent for drought relief projects.
1996	Hawaii, Maui, and Molokai	Declared drought emergency; heavy damages to agriculture and cattle industries; Losses totaling at least $9.4 million.
1998 – 1999	Hawaii and Maui	State declared drought emergency for Maui; County declared emergency for Hawaii due to water shortages; heavy damages to agriculture and cattle industries; Statewide cattle losses alone estimated at $6.5 million.
2000 – 2002	Hawaii, Maui, Molokai, Oahu, Kauai	Counties declare drought emergencies; Governor proclaims statewide drought emergency; Secretary of Interior designates all Counties as primary disaster areas due to drought; East Maui streams at record low levels; Statewide cattle losses alone projected at $9 million.

Source: Hawaii Drought Monitor, Commission of Water Resource Management.
http://www.state.hi.us/dlnr/cwrm/drought/history.htm

Table 2.10 Island of Hawaii Drought Frequency and Severity (BMDI)

Event	Drought Event						
Rank	From		To		Severity	Magnitude	Duration (Mo)
1	1980	Dec	1981	Jul	-21.08	-2.64	8
2	1971	Jun	1971	Oct	-13.5	-2.70	5
3	1953	Aug	1953	Nov	-11.32	-2.83	4
4	1983	Jan	1983	Apr	-11.25	-2.81	4
5	1973	Jun	1973	Aug	-9.32	-3.11	3
6	1962	Oct	1962	Dec	-8.23	-2.74	3
7	1943	Nov	1944	Jan	-7.99	-2.66	3
8	1933	Aug	1933	Oct	-7.59	-2.53	3
9	1939	Dec	1940	Feb	-7.17	-2.39	3
10	1941	Feb	1941	Apr	-6.84	-2.28	3
11	1977	Nov	1977	Dec	-5.64	-2.82	2
12	1977	Jan	1977	Feb	-5.56	-2.78	2
13	1969	Oct	1969	Nov	-5.15	-2.57	2
14	1975	Jun	1975	Jul	-5.13	-2.57	2
15	1970	Feb	1970	Mar	-5.11	-2.56	2
16	1949	Apr	1949	May	-5.07	-2.54	2
17	1984	Sep	1984	Oct	-5.03	-2.52	2
18	1976	Aug	1976	Sep	-4.92	-2.46	2
19	1961	Aug	1961	Sep	-4.69	-2.35	2
20	1932	Oct	1932	Nov	-4.61	-2.30	2
* These records are from a complete rain-gage network, February 1931 to December 1986							
1	1826	Nov	1897	Jul	-27.08	-3.01	9
2	1925	Dec	1926	May	-17.69	-2.95	6
3	1894	May	1894	Oct	-16.01	-2.67	6
4	1899	Dec	1900	Apr	-13.82	-2.76	5
5	1904	Dec	1905	Apr	-11.96	-2.39	5
6	1919	Apr	1919	Jul	-9.60	-2.40	4
7	1898	Nov	1899	Feb	-9.53	-2.38	4
8	1920	May	1920	Aug	-8.63	-2.16	4
9	1917	Jul	1917	Sep	-8.32	-2.77	3
10	1931	Jan	1931	Mar	-8.07	-2.69	3
11	1906	Feb	1906	Apr	-7.97	-2.66	3
12	1893	Aug	1893	Oct	-7.42	-2.47	3
13	1901	Jun	1901	Aug	-7.12	-2.37	3
14	1892	Apr	1892	May	-5.94	-2.97	2
15	1922	Jun	1922	Jul	-5.30	-2.65	2
16	1919	Nov	1919	Dec	-5.22	-2.61	2
17	1921	May	1921	Jun	-5.04	-2.52	2
18	1912	Aug	1912	Sep	-4.67	-2.33	2
19	1913	Mar	1913	Apr	-4.62	-2.31	2
20	1907	Dec	1908	Jan	-4.22	-2.11	2
** These records are from an incomplete rain-gage network (Min. 50% of Network),							
February 1890 to January 1931							

Source: Giambelluca, T.W., et. al., 1991. Drought in Hawaii, Report R88. State of Hawaii, Department of Land and Natural Resources, Commission on Water Resource Management

Table 2.11 Island of Maui Drought Frequency and Severity (BMDI)

Event	Drought Event						
Rank	From		To		Severity	Magnitude	Duration (Mo)
1	1971	Jun	1972	Jan	-21.06	-2.63	8
2	1953	Jul	1954	Feb	-20.44	-2.55	8
3	1984	Jun	1985	Jan	-20.01	-2.5	8
4	1977	Sep	1978	Feb	-15.91	-2.65	6
5	1933	Jul	1933	Nov	-15.18	-3.04	5
6	1926	Feb	1926	May	-12.04	-3.01	4
7	1943	Oct	1944	Jan	-11.28	-2.82	4
8	1976	Dec	1977	Feb	-9.60	-3.20	3
9	1975	Apr	1975	Jul	-9.54	-2.38	4
10	1922	Jun	1922	Aug	-8.90	-2.97	3
11	1983	Jan	1983	Mar	-8.52	-2.84	3
12	1973	Jul	1973	Sep	-8.47	-2.82	3
13	1980	Nov	1981	Jan	-8.08	-2.69	3
14	1949	Aug	1949	Oct	-8.02	-2.67	3
15	1931	Jan	1931	Mar	-7.83	-2.61	3
16	1966	Apr	1966	Jun	-7.56	-2.52	3
17	1932	Oct	1932	Dec	-6.21	-2.07	3
18	1945	Jan	1945	Feb	-6.21	-3.10	2
19	1962	Oct	1962	Nov	-5.92	-2.96	2
20	1975	Dec	1976	Jan	-5.38	-2.69	2
21	1935	Dec	1936	Jan	-5.33	-2.66	2
22	1946	May	1946	Jun	-4.78	-2.39	2
23	1949	Apr	1949	May	-4.71	-2.35	2
24	1976	May	1976	Jun	-4.30	-2.15	2
* These records are from a complete rain-gage network, January 1922 to December 1986							
1	1912	May	1912	Sep	-13.23	-2.64	5
2	1917	Jul	1917	Sep	-7.49	-2.50	3
3	1907	Dec	1908	Jan	-5.51	-2.76	2
4	1919	Nov	1919	Dec	-5.11	-2.55	2
5	1905	Jan	1905	Feb	-4.87	-2.43	2
** These records are from an incomplete rain-gage network (Min. 50% of Network),							

Source: Giambelluca, T.W., et. al., 1991. Drought in Hawaii, Report R88. State of Hawaii, Department of Land and Natural Resources, Commission on Water Resource Management

Table 2.12 Island of Molokai Drought Frequency and Severity (BMDI)

Event	Drought Event						
Rank	From		To		Severity	Magnitude	Duration (Mo)
1	1933	Apr	1933	Nov	-23.16	-2.89	8
2	1953	Jul	1954	Feb	-21.9	-2.74	8
3	1941	Feb	1941	Sep	-19.86	-2.48	8
4	1971	Jul	1972	Jan	-18.90	-2.70	4
5	1984	Jul	1984	Dec	-17.24	-2.87	6
6	1977	Oct	1978	Feb	-15.28	-3.06	5
7	1952	Dec	1953	Apr	-13.83	-2.77	5
8	1949	Sep	1949	Dec	-11.55	-2.89	4
9	1964	Feb	1964	Jun	-11.07	-2.21	5
10	1943	Oct	1944	Jan	-10.89	-2.72	4
11	1935	Nov	1936	Feb	-10.42	-2.61	4
12	1930	May	1930	Aug	-10.37	-2.59	4
13	1931	Jan	1931	Mar	-10.30	-3.43	3
14	1945	Jan	1945	Mar	-10.11	-3.37	3
15	1946	Mar	1946	Jun	-9.38	-2.35	4
16	1949	Mar	1949	Jun	-9.29	-2.32	4
17	1932	Nov	1933	Jan	-8.66	-2.89	3
18	1983	Mar	1983	May	-7.76	-2.59	3
19	1976	Dec	1977	Jan	-7.31	-3.66	2
20	1947	Feb	1947	Apr	-7.29	-2.43	3
21	1941	Dec	1942	Jan	-6.94	-3.47	2
22	1975	Dec	1976	Jan	-6.86	-3.43	2
23	1952	Aug	1952	Sep	-5.47	-2.73	2
24	1952	Mar	1952	Apr	-5.35	-2.68	2
25	1945	Oct	1945	Nov	-4.85	-2.42	2
26	1939	Jul	1939	Aug	-4.79	-2.39	2
27	1942	May	1942	Jun	-4.55	-2.27	2
28	1979	Sep	1979	Oct	-4.31	-2.16	2
* These records are from a complete rain-gage network, February 1930 to December 1986							
1	1928	Sep	1928	Dec	-12.05	-3.01	4
2	1921	May	1921	Sep	-11.55	-2.31	5
3	1912	Dec	1913	Feb	-10.90	-3.63	3
4	1926	Feb	1926	May	-10.70	-2.68	4
5	1919	Dec	1920	Mar	-10.41	-2.60	4
6	1901	Aug	1901	Nov	-10.24	-2.56	4
7	1908	Oct	1909	Jan	-10.22	-2.56	4
8	1922	May	1922	Aug	-9.53	-2.38	4
9	1907	Dec	1908	Feb	-9.29	-3.10	3
10	1911	Nov	1912	Jan	-8.67	-2.89	3
11	1905	Feb	1905	Mar	-6.19	-3.10	2
12	1929	Mar	1929	Apr	-5.36	-2.68	2
13	1920	Sep	1920	Oct	-5.27	-2.63	2
14	1925	Feb	1925	Mar	-4.25	-2.12	2
** These records are from an incomplete rain-gage network (Min. 50% of Network), February 1900 to January 1930							

Source: Giambelluca, T.W., et. al., 1991. Drought in Hawaii, Report R88. State of Hawaii, Department of Land and Natural Resources, Commission on Water Resource Management

Table 2.13 Island of Lanai Drought Frequency and Severity (BMDI)

Event	Drought Event						
Rank	From		To		Severity	Magnitude	Duration (Mo)
1	1975	May	1976	Jan	-26.07	-2.9	9
2	1977	Aug	1978	Mar	-22.92	-2.86	8
3	1953	May	1953	Nov	-21.28	-3.04	7
4	1949	Aug	1950	Mar	-21	-2.63	8
5	1941	Jan	1941	Jul	-17.1	-2.44	7
6	1928	Aug	1928	Dec	-15.11	-3.02	5
7	1944	Nov	1945	Mar	-14.15	-2.83	5
8	1952	Apr	1952	Sep	-12.78	-2.13	6
9	1973	Jun	1973	Oct	-11.47	-2.29	5
10	1983	Feb	1983	Jun	-11.03	-2.21	5
11	1946	Mar	1946	Jun	-10.97	-2.74	4
12	1926	Feb	1926	May	-10.67	-2.67	4
13	1976	Dec	1977	Feb	-10.51	-3.5	3
14	1933	Sep	1933	Nov	-10.05	-3.35	3
15	1959	Dec	1960	Feb	-9.37	-3.12	3
16	1952	Dec	1953	Feb	-8.72	-2.91	3
17	1938	Nov	1939	Feb	-8.63	-2.16	4
18	1949	Mar	1949	May	-7.69	-2.56	3
19	1931	Jan	1931	Feb	-7.36	-3.68	2
20	1969	Sep	1969	Nov	-7.33	-2.44	3
21	1941	Dec	1942	Jan	-6.45	-3.22	2
22	1973	Feb	1973	Mar	-6.31	-3.16	2
23	1962	Aug	1962	Sep	-6.17	-3.08	2
24	1931	Dec	1932	Jan	-5.87	-2.94	2
25	1984	Sep	1984	Oct	-5.77	-2.89	2
26	1971	Nov	1971	Dec	-5.66	-2.83	2
27	1957	Sep	1957	Oct	-5.54	-2.77	2
28	1971	Jun	1971	Jul	-5.49	-2.75	2
29	1950	Sep	1950	Oct	-5.35	-2.67	2
30	1930	May	1930	Jun	-5.34	-2.67	2
31	1983	Oct	1983	Nov	-5.27	-2.63	2
32	1970	Sep	1970	Oct	-5.21	-2.61	2
33	1980	Oct	1980	Nov	-5.19	-2.59	2
34	1964	May	1964	Jun	-5.12	-2.56	2
35	1970	Mar	1970	Apr	-5.06	-2.53	2
36	1959	Jun	1959	Jul	-4.94	-2.47	2
37	1944	Jul	1944	Aug	-4.9	-2.45	2
38	1985	Mar	1985	Apr	-4.83	-2.42	2
39	1966	Jul	1966	Aug	-4.81	-2.4	2
40	1969	Apr	1969	May	-4.74	-2.37	2
41	1981	Mar	1981	Apr	-4.72	-2.36	2
42	1925	Apr	1925	May	-4.52	-2.26	2
43	1928	Feb	1928	Mar	-4.48	-2.24	2
* These records are from a complete rain-gage network, February 1924 to December 1986							

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Event	Drought Event						
Rank	**From**		**To**		**Severity**	**Magnitude**	**Duration (Mo)**
1	1919	Jul	1920	Mar	-28.89	-3.21	9
2	1906	Feb	1906	Sep	-21.85	-2.73	8
3	1912	Sep	1913	Feb	-19.06	-3.18	6
4	1923	Oct	1924	Mar	-13.22	-2.2	6
5	1918	Dec	1919	Mar	-12.8	-3.2	4
6	1911	Nov	1912	Jan	-9.41	-3.14	3
7	1896	Apr	1896	Jun	-8.76	-2.92	3
8	1897	Feb	1897	Apr	-8.01	-2.67	3
9	1916	Sep	1916	Nov	-7.26	-2.42	3
10	1895	Mar	1895	Apr	-4.86	-2.43	2
11	1915	Jan	1915	Feb	-4.71	-2.36	2
** These records are from an incomplete rain-gage network (Min. 50% of Network), February 1892 to January 1924							

Source: Giambelluca, T.W., et. al., 1991. Drought in Hawaii, Report R88. State of Hawaii, Department of Land and Natural Resources, Commission on Water Resource Management

Table 2.14 Island of Oahu Drought Frequency and Severity (BMDI)

Event	Drought Event						
Rank	From		To		Severity	Magnitude	Duration (Mo)
1	1983	Nov	1984	Oct	-31.48	-2.62	12
2	1953	Apr	1954	Jan	-27.55	-2.75	10
3	1977	Aug	1978	Mar	-24.49	-3.06	8
4	1944	Aug	1945	Mar	-20.94	-2.62	8
5	1976	Aug	1977	Feb	-20.84	-2.98	7
6	1975	Ma	1975	Oct	-17.55	-2.92	6
7	1926	Jan	1926	May	-15.63	-3.13	5
8	1943	Sep	1944	Jan	-14.63	-2.93	5
9	1941	Jan	1941	May	-14.45	-2.89	5
10	1933	Aug	1933	Nov	-12.53	-3.13	4
11	1983	Feb	1983	May	-10.31	-2.58	4
12	1931	Jan	1931	Apr	-10.21	-2.55	4
13	1979	Jul	1979	Oct	-9.90	-2.48	4
14	1973	Jan	1973	Apr	-9.76	-2.44	4
15	1949	Sep	1949	Nov	-9.36	-3.12	3
16	1968	Jun	1968	Aug	-8.30	-2.77	3
17	1985	Dec	1986	Feb	-8.20	-2.73	3
18	1959	Dec	1960	Feb	-7.38	-2.46	3
19	1923	Jun	1923	Aug	-7.34	-2.45	3
20	1959	Jun	1959	Jul	-6.05	-3.03	2
21	1941	Dec	1942	Jan	-5.76	-2.88	2
22	1946	Apr	1946	May	-5.51	-2.76	2
23	1926	Nov	1926	Dec	-5.33	-2.66	2
24	1957	Sep	1957	Oct	-5.29	-2.64	2
25	1919	Feb	1919	Mar	-5.25	-2.62	2
26	1946	Sep	1946	Oct	-5.19	-2.59	2
27	1949	Apr	1949	May	-5.07	-2.54	2
28	4952	Aug	1952	Sep	-5.00	-2.50	2
29	1963	Nov	1963	Dec	-4.83	-2.42	2
30	1972	Jul	1972	Aug	-4.81	-2.40	2
31	1961	Mar	1961	Apr	-4.80	-2.40	2
32	1952	Dec	1953	Jan	-4.74	-2.37	2
33	1922	Jun	1922	Jul	-4.48	-2.24	2
34	1973	Aug	1973	Sep	-4.40	-2.20	2
35	1929	Mar	1929	Apr	-4.37	-2.18	2

* These records are from a complete rain-gage network, February 1931 to December 1986

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Event	Drought Event						
Rank	From		To		Severity	Magnitude	Duration (Mo)
1	1888	Dec	1889	May	-16.44	-2.74	6
2	1899	Nov	1900	Mar	-14.41	-2.88	5
3	1891	Mar	1891	Aug	-13.34	-2.22	6
4	1897	Feb	1897	May	-10.48	-2.62	4
5	1886	Jan	1886	Apr	-10.39	-2.60	4
6	1898	Nov	1899	Jan	-8.27	-2.76	3
7	1915	Jan	1915	Mar	-8.03	-2.68	3
8	1894	Jul	1894	Sep	-7.65	-2.55	3
9	1905	Feb	1905	Mar	-5.91	-2.95	2
10	1885	Jan	1885	Feb	-5.86	-2.93	2
11	1908	Nov	1908	Dec	-5.68	-2.84	2
12	1908	Jul	1908	Aug	-5.24	-2.62	2
13	1893	Jul	1893	Aug	-4.95	-2.48	2
14	1891	Nov	1891	Dec	-4.43	-2.22	2
15	1912	May	1912	Jun	-4.40	-2.20	2

** These records are from an incomplete rain-gage network (Min. 50% of Network), January 1895 to January 1931

Source: Giambelluca, T.W., et. al., 1991. Drought in Hawaii, Report R88. State of Hawaii, Department of Land and Natural Resources, Commission on Water Resource Management

Table 2.15 Island of Kauai Drought Frequency and Severity (BMDI)

Event	Drought Event						
Rank	From		To		Severity	Magnitude	Duration (Mo)
1	1953	Apr	1953	Nov	-22.96	-2.87	8
2	1983	Dec	1984	Aug	-22.92	-2.55	9
3	1975	May	1975	Oct	-20.55	-3.43	6
4	1944	Sep	1945	Mar	-19.92	-2.85	7
5	1977	Sep	1978	Mar	-18.81	-2.69	7
6	1931	Jan	1931	Jul	-16.46	-2.35	7
7	1919	Jan	1919	Jun	-16.03	-2.67	6
8	1976	Oct	1977	Feb	-13.96	-2.79	5
9	1949	Jul	1949	Nov	-13.5	-2.7	5
10	1933	Aug	1933	Nov	-12.72	-3.18	4
11	1926	Feb	1926	May	-12	-3	4
12	1973	Jun	1973	Sep	-11.4	-2.85	4
13	1941	Jan	1941	Apr	-10.23	-2.56	4
14	1983	Feb	1983	Apr	-9.76	-3.25	3
15	1911	Dec	1912	Mar	-9.7	-2.43	4
16	1985	Dec	1986	Feb	-9.54	-3.18	3
17	1958	Mar	1958	Jun	-9.34	-2.33	4
18	1915	Jan	1915	Mar	-8.8	-2.93	3
19	1972	Dec	1973	Feb	-7.88	-2.63	3
20	1966	Mar	1966	May	-7.84	-2.61	3
21	1943	Nov	1944	Jan	-7.69	-2.56	3
22	1912	Sep	1912	Nov	-7.08	-2.36	3
23	1963	Nov	1963	Dec	-6.98	-3.49	2
24	1979	Jul	1979	Sep	-6.94	-2.31	3
25	1921	Jul	1921	Aug	-5.78	-2.89	2
26	1951	Jun	1951	Jul	-5.71	-2.85	2
27	1957	May	1957	Jun	-5.67	-2.84	2
28	1959	Mar	1959	Apr	-5.34	-2.67	2
29	1946	Sep	1946	Oct	-5.31	-2.66	2
30	1962	Nov	1962	Dec	-5.26	-2.63	2
31	1934	Feb	1934	Mar	-5.16	-2.58	2
32	1952	Aug	1952	Sep	-5.16	-2.58	2
33	1924	Aug	1924	Sep	-5.14	-2.57	2
34	1930	Apr	1930	May	-5.01	-2.51	2
35	1922	Jun	1922	Jul	-4.91	-2.46	2
36	1941	Dec	1942	Jan	-4.7	-2.35	2
37	1935	Apr	1935	May	-4.65	-2.33	2
38	1938	Dec	1939	Jan	-4.46	-2.23	2
39	1952	Dec	1953	Jan	-4.41	-2.21	2
* These records are from a complete rain-gage network, February 1931 to December 1986							

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Event	Drought Event						
Rank	From		To		Severity	Magnitude	Duration (Mo)
1	1898	Sep	1899	Feb	-18.45	-3.07	6
2	1894	May	1894	Oct	-15.53	-2.59	6
3	1906	Feb	1906	Jul	-14.2	-2.37	6
4	1891	Jan	1891	May	-14.09	-2.82	5
5	1905	Jan	1905	Apr	-11.05	-2.76	4
6	1900	Mar	1900	Jun	-10.49	-2.62	4
7	1908	Nov	1909	Jan	-9.1	-3.03	3
8	1895	Mar	1895	May	-8.05	-2.68	3
9	1899	Jul	1899	Sep	-7.26	-2.42	3
10	1903	Nov	1904	Jan	-6.28	-2.09	3
11	1893	Jul	1893	Aug	-5.2	-2.6	2
12	1903	Feb	1903	Mar	-4.96	-2.48	2
13	1910	Mar	1910	Apr	-4.33	-2.16	2
** These records are from an incomplete rain-gage network (Min. 50% of Network), January 1895 to January 1931							

Source: Giambelluca, T.W., et. al., 1991. Drought in Hawaii, Report R88. State of Hawaii, Department of Land and Natural Resources, Commission on Water Resource Management

3. STATEWIDE DROUGHT FREQUENCY ANALYSIS

3.1 BACKGROUND

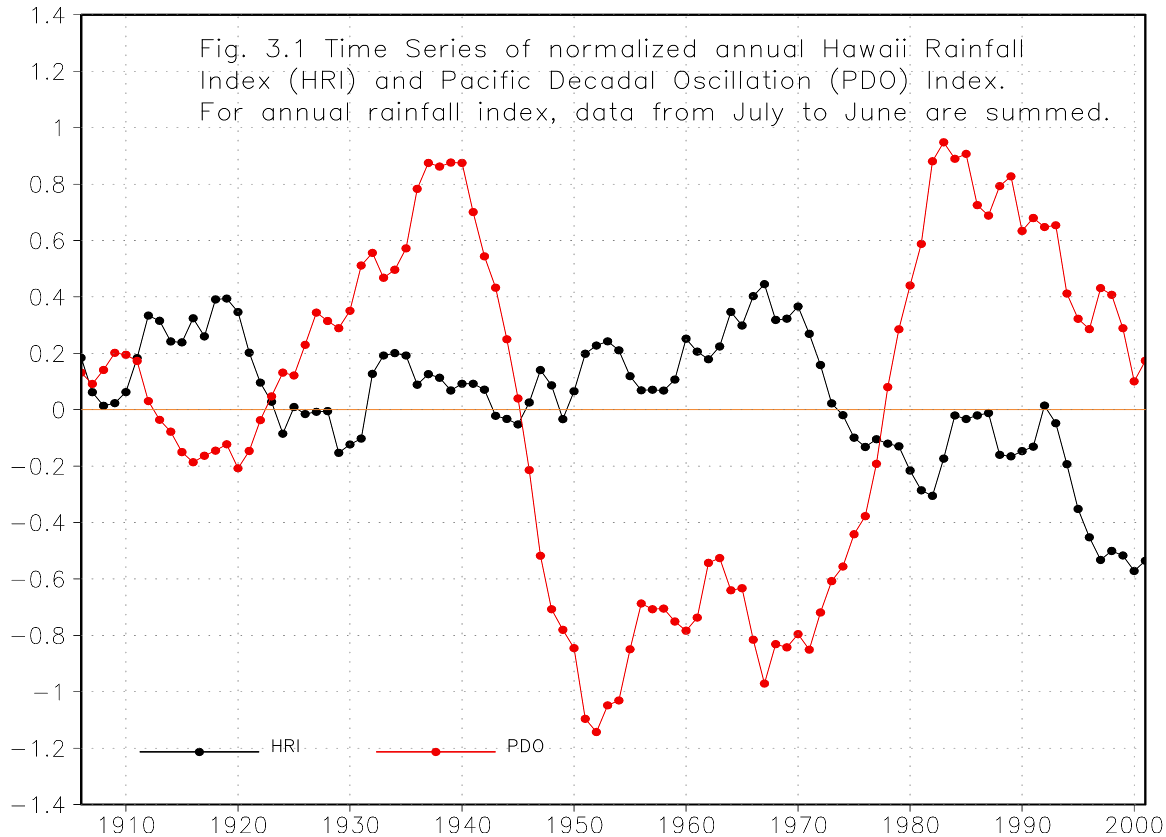
Giambelluca et al. (1990) compiled a comprehensive listing of historical drought events in Hawaii using data up to 1986. Based on the Bhalme and Mooley method to define drought severity, they ranked the drought into several stages. In that report, the beginning and ending dates, as well as the magnitude and duration, of each drought event were given (Section 2.5). The most severe drought occurred from September 1977 to February 1978, lasting six months. This was followed by another severe event in 1975, also with duration of six months. From 1931 to 1986 (56 years), 17 drought events were identified. They noted that no statewide drought event exceeded six months and the overall recurrence interval for statewide drought is about 3.3 years. One interesting result from their study is that drought frequency is not invariant but changing with time. The 1970s and 1980s were marked by a high frequency of drought incidences. For instance, a total of eight drought events were identified during a 16-year period from 1971 to 1986. On average, that equates to one event occurring every other year.

From a meteorological perspective, drought in Hawaii has been a subject of intense research since the 1970s. Wright (1979) found a simultaneous, negative correlation between sea-surface temperatures in the equatorial eastern Pacific and winter rainfall at Honolulu International Airport. Horel and Wallace (1981) proposed a conceptual model to relate dryness in the Hawaiian Islands with the Southern Oscillation (SO), a large-scale pressure see-saw effect observed across the tropical Pacific. Their analysis attributed drought in Hawaii to the enhancement and southward displacement of the North Pacific jet stream during winters when the SO reaches its extremely low phase. This corresponds to an anomalous warming of the tropical Pacific Ocean, known as El Niño. The El Niño is coupled to the SO and both events are labeled collectively ENSO. Moving one step further, Chu (1989) examined the temporal lead-lag correlations between the SO and Hawaiian rainfall and developed a simple model for predicting Hawaiian winter rainfall with a lead of two seasons.

Chu (1995) further refined the El Niño and Hawaiian rainfall relationship by compositing historical rainfall variations through an El Niño cycle. Based on 20 El Niño events since 1905, this study showed that the chance of having a dry winter (spring) following an onset of El Niño was 90% (80%). Monte Carlo simulation tests indicate that deficient rainfall observed during an El Niño winter is unlikely to have occurred by random chance. Considerations about how El Niño affects island rainfall follow. At the height of El Niño, warm pools of ocean water and enhanced convection are found over the equatorial central Pacific. This leads to strong Hadley-type circulation over the Central Pacific. Because Hawaii is located in the sinking branch of the Hadley cell, synoptic systems such as Kona storms and the mid-latitude frontal rainbands that usually produce cool-season rainfall have become unfavorable, thus producing drought conditions. Moreover, the strong equatorial heating associated with El Niño results in a stronger and an eastward extension of the upper-level subtropical jet stream over the North Pacific. Hawaii is located under the right-hand exit region of the jet, which favors divergence at the lower troposphere. Thus, the anomalous displacement of the jet and the development of the Hadley circulation are two important features that inhibit rainfall production in Hawaii.

Rainfall in Hawaii is not only affected by inter-annual climate variations such as ENSO but also by a longer time scale variation known as the Pacific Decadal Oscillation (PDO). Figure 3.1 displays the Hawaii Rainfall Index (HRI), defined as the normalized rainfall anomalies averaged from three islands (Hawaii, Oahu, and Kauai) and the PDO since the turn of the last century. The PDO is taken as the leading eigenmode[3] of the North Pacific sea-surface temperatures (Mantua et al. 1997).   The decadal mode may be regarded as a slowly varying mean climate state with a period of 30 to 40 years. In order to capture low-frequency variability, an 11-year running mean is applied to both series. Generally speaking, an out-of-phase relationship between the two series is seen. For example, during 1946-1977 when the PDO was in the negative phase, rainfall was above normal in Hawaii. Conversely, since 1977 when the PDO was in the positive phase, Hawaii rainfall tended to be below normal. For the entire period (1906-2001), a negative correlation (-0.49) is found between rainfall index and the PDO, and this correlation is statistically significant at the 1% level. Therefore, the shifting climate regime over the North Pacific since the late 1970s has caused an unfavorable condition for rainfall in Hawaii. The causes of PDO-induced drought are still unclear and will warrant future investigations.

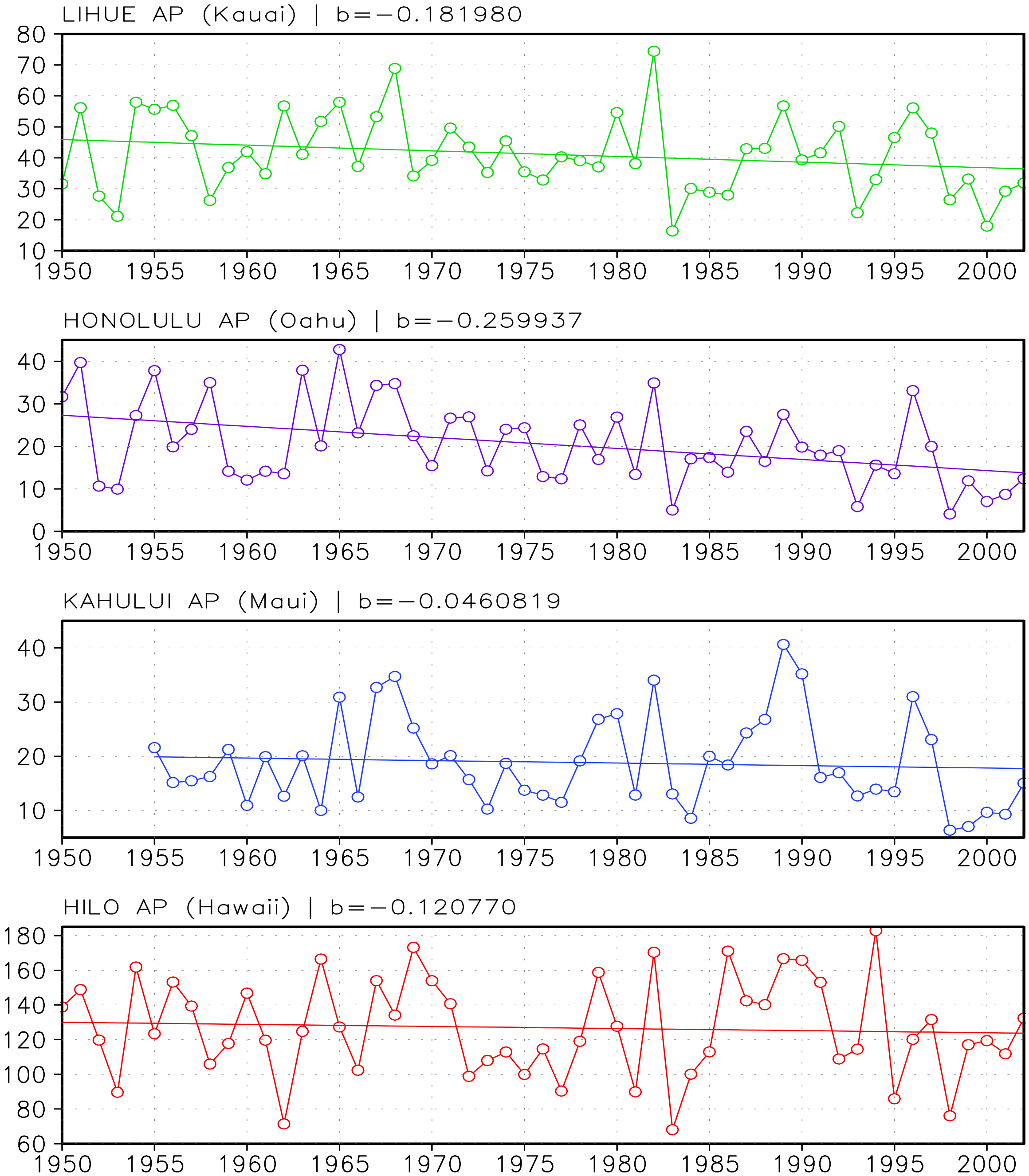
Figure 3.1 Times Series of Normalized Annual HRI and PDO



When one examines rainfall trends in recent years, one notes a clear downward trend. This is illustrated in Figure 3.2 for airport stations on four different islands.   All four airports have experienced less and less rainfall over the time and rainfall has been particularly low during the last 20 years or so. The most pronounced decreasing trend is exhibited at Honolulu Airport, where the trend (-0.26) is statistically significant at the 5% level.   Lihue Airport also saw a significant downward trend in rainfall. This result should not be surprising given that the PDO has changed its phase as discussed previously.

[3] http://richter.colorado.edu/~sethmc/thesis/node12.html

Figure 3.2 Time Series of Annual Rainfall (inches) at Four Major Airports in Hawaii



b. refers to the linear regression trend.

3.2 PURPOSE AND METHODOLOGY

The purpose of the Drought Frequency Analysis is to determine the frequency and severity of drought in Hawaii and graphically represent the spatial distribution of drought occurrences county by county. The resultant frequency data are intended for integration with the results of the drought vulnerability analysis to identify areas subject to drought risk.

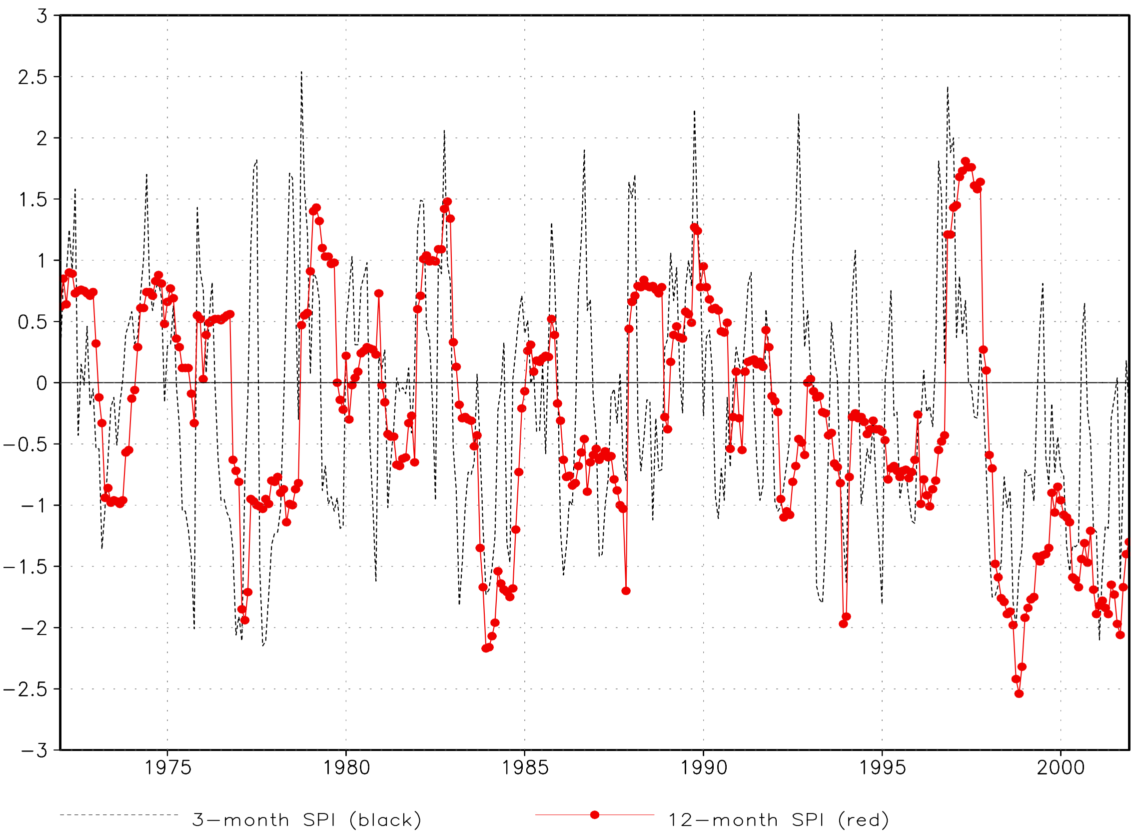
Traditionally, the Palmer Drought Index (PDI) has been used as an indicator of drought severity in the U.S. The PDI computation involves precipitation, evapotranspiration, runoff, and soil moisture. Although the PDI has been used by water managers in an operational setting, it is not practical to implement it in Hawaii because of very limited information on soil moisture and evapotranspiration. In this project, we adopted the Standardized Precipitation Index (SPI) method, which was developed by McKee et al. (1993) to define rainfall deficit for different time scales. In contrast to the PDI which relies on several variables for a water balance accounting scheme, the SPI requires only a single variable (precipitation). This is the major advantage in the context of the rather dense rain gage network and the sparse or non-existent soil moisture records in Hawaii.

We will not go over the details of the derivation of SPI but suffice to say that it involves the fitting of an incomplete gamma distribution to the precipitation series and a transformation to the standard Gaussian distribution. SPI values are negative for less than median precipitation. Because we are concerned with drought, negative SPI values are of interest. The departure from zero on the left half of the standard Gaussian distribution is indicative of the severity of drought. The larger the departure, the more severe is the drought. According to the National Drought Mitigation Center in Lincoln, Nebraska, a drought classification scheme based on SPI has been developed (Table 3.1). Depending on the SPI value, four stages of drought are defined (i.e., mild, moderate, severe, and extreme). Given that the impact of mild drought on socio-economic sectors is relatively mild, we will consider the other three stages.

The SPI method is designed to be flexible in terms of drought duration specified by users. Short time scales (e.g., 3 months) may be important for agricultural practices while long time scales (e.g., one year or longer) may be vital for water supply management interests. In this project, 3-month, 12-month, and 24-month time scales are considered. For the 3-month SPI, drought duration is considered. Rather than using any 3-month SPI values individually, we constrained the analysis by considering at least two consecutive time periods when the SPI values are less than -1.00 as a drought event. For example, if the 3-month SPI values for two consecutive periods are between -1 and -1.49, a moderate drought event is counted.

The construction of SPI for various durations is as follows. If three-month events are desired, a time series is constructed by summing the first three monthly totals. Next, precipitations for months 2, 3, and 4 are summed and then precipitations for months 3, 4, and 5 are summed and so on. The resulting time series is then used to compute the 3-month SPI. The 12-month and 24-month SPI can be obtained in the same manner. Figure 3.3 shows an example of the 3-month and 12-month SPI time series at Honolulu International Airport. Note that the 3-month SPI series exhibits by a high frequency variation. Applying a 12-month SPI method is a smoothing operation so that shorter wavelengths in a series (i.e., high frequency waves) are filtered out. The flexibility of multiple SPI time values makes this index attractive because drought affects various sectors across a wide range of time scales.

Figure 3.3 The 3-Month and 12-Month SPI Series at Honolulu International Airport (1972 - 2001)



3.3 ASSUMPTIONS

This component of the study attempts to analyze drought frequency for three time scales of SPI for moderate, severe, and extreme categories (Table 3.1) because of their larger magnitudes relative to mild drought stage. It is expected that the impacts of these categories on various sectors are more evident. For SPI computations, the historical, monthly precipitation records up to 2001 were downloaded from the NOAA/National Climatic Data Center (NCDC) website. The analysis is performed for two 30-year periods – 1942-1971 and 1972-2001(Table 3.2). The 30-year period is commonly considered as a normal epoch by the World Meteorological Organization in Geneva, Switzerland. The year 2001 is included in the second batch because low rainfall in Hawaii occurred consecutively during the last few years. The latter 30-year period (1972-2001) is chosen for subsequent discussions because it is closer to the current climate and most GIS data are relevant to this period.

Table 3. 1 Drought Classification Based on SPI

SPI values	Designation	Expected freq occurrence (%)
0.00 to -0.99	Mild Drought	34.2
-1.00 to -1.49	Moderate Drought	9.1
-1.50 to -1.99	Severe Drought	4.4
-2.00 or less	Extreme Drought	2.3

Table 3.2 Number of Rain Gages Used on Each Island for a 30-Year Period

Island	1942-1971 Number of gages	1972-2001 Number of gages
Hawaii	86	53
Maui	56	50
Lanai	3	6
Molokai	6	5
Oahu	54	44
Kauai	52	36

3.4 DROUGHT FREQUENCY MAPS AND DICUSSION OF RESULTS

In the following discussion, we will discuss the drought frequency maps for each county based on the three-month and twelve-month SPI for two drought severity levels (moderate and severe). These will serve as prelude to the drought vulnerability analysis described in Section 4 and the drought risk assessment to be described in section 5. We will not discuss the extreme drought stage in this subsection because of its low frequency of occurrence. However, in section 5, this particular drought stage will be included for the completeness of risk and vulnerability assessment across a spectrum of drought severity levels.

3.4.1 3-MONTH SPI

For the 3-month SPI, the moderate drought stage will be discussed first. For the County of Hawaii (Figure 3.4), the areas of higher frequency (i.e., greater than 8%) are concentrated along the southern coast, north of Kona, Hilo, and Kohala. For Maui, the eastern tip and two small north-facing pockets are vulnerable to drought. Southern Lanai has experienced drought during the last 30 years, and so has the western, drier side of Molokai. The most notable feature for Oahu is an elongated area of high drought frequency extending from Ewa and Honolulu Airport northward through the central valley. The eastern tip of Oahu, including Hawaii Kai, also shows sign of drought, and so does the Kaneohe area (Figure 3.5). For Kauai, areas with high frequency are found in the interior and within two small belts on the eastern shore.

The next drought stage to be discussed is the severe drought. Because the expected frequency of this drought stage is less than half of the moderate drought (Table 3.1), the shading used for highlighting frequency for severe drought is reduced to 4% and above (Figure 3.6). Also the contour interval in severe drought category is half that of the moderate stage. For the island of Hawaii, a large band of high frequency extends from the north Kona coast through south Kona to Kau. The north shores from Hamakua to Hilo districts, where rainfall is generally high, experienced higher frequency of severe drought. A third area of high drought frequency is found over the Puna coast. The eastern tip and north shores of east Maui saw high frequency of severe drought. Notably, this is also the area where moderate drought prevails (Figure 3.4). West Maui, eastern Molokai, and southern Lanai are also marked by a relatively high frequency of severe drought. The interior of Oahu appears to have experienced severe drought conditions in the last 30 years (Figure 3.7). For Kauai, a severe drought-prone region from Hanalei to central Kauai coincides with the area where the climatological median annual rainfall is high (exceeding 2000 mm).

3.4.2 12-MONTH SPI

For moderate drought, the contour shading starts from 16% and the contour interval is 8%. Many areas in west Hawaii from Kohala through Kona to Kau experienced a high frequency of the moderate drought stage, with the maximum value as large as 32% (Figure 3.8). Maui also saw a large area where the drought frequency exceeds 16%. In particular, a large swatch of high frequency is conspicuous over central Maui including Kahului and Waikulu. The interior Oahu and Kauai (Figure 3.9) are also marked by a high frequency of drought.

Again, because of the relatively fewer occurrences of severe drought compared to moderate drought, the contour interval is reduced to 4% and shading starts from 8%. Many districts on the island of Hawaii became vulnerable to severe drought during the last 30 years (Figure 3.10). These include north Kona, south Kona, Kau, Puna, north Hilo, and a portion of Hamakua. In some districts, the maximum frequency reaches 16%. All three islands in the County of Maui experienced a relatively high frequency of severe drought. Oahu is also marked by a relatively high frequency of severe drought, in particular the saddle area between Koolau and Waianae mountains near Mililani and Haleiwa (Figure 3.11). Likewise, Kauai became vulnerable to severe drought in areas where climatological rainfall is high.

3.4.3 CAVEATS AND DATA LIMITATIONS/DEFICIENCIES

Because the SPI computation transforms the original precipitation records from a gamma distribution to the Gaussian distribution, the resulting frequencies for each drought stage tend to reach their climatological expectations. That is, the drought frequencies for each stage among all gages would be very similar, resulting in small spatial gradients of drought frequency. This restricts the portrait of absolute frequency of drought occurrence at each gage and is an inherent problem in spatial analysis when the SPI method is used. Another concern includes the drought stages based on different SPI values. For example, a severe drought is declared if the SPI falls between -1.50 and -1.99. If the computed SPI is -1.49, then it is not in the severe category but this value is virtually indistinguishable from -1.50.

The number of rain gages and their density also merits mention. Table 3.2 lists the number of gages selected for six Hawaiian Islands for each 30-year period. In all, 257 gages are used during 1942-1971 and 194 gages are used during 1972-2001 (Figs. 3.12 and 3.13). Except for the island of Lanai, all five islands saw a decrease in rain gages from the early to the latter period. In particular, the island of Hawaii lost 33 gages (a reduction of 38%) from the first to the second epoch. This is unfortunate because the island of Hawaii is relatively large and more gages would be needed in order to resolve the large spatial variability in rainfall. Consequently, there are conspicuous gaps in the rain gage network in the island interior (Figure 3.13). The number of rain gages in Molokai and Lanai is quite limited so the analyzed drought frequencies are subject to a degree of uncertainty. For Oahu, the western portion of the island shows data gaps. Likewise, the interior Kauai suffers from inadequate coverage. The data coverage problems may be overcome if the state data from the Hawaii State Climate Office, University of Hawaii, are used. These data, while unconnected to the NCDC network, are only available on hard copy so compilation and digitization are required.

The interpolation method used to create frequency contours is based on the Spline analysis that is available in most GIS software. Spline analysis minimizes the overall surface curvature so that a smooth surface passes through the input grids. There are two Spline methods and the Regularized method is chosen because it creates a smooth, gradually varying surface.

Figure 3.4 Drought Frequency - 3-Month SPI, Moderate Drought (Hawaii and Maui County)

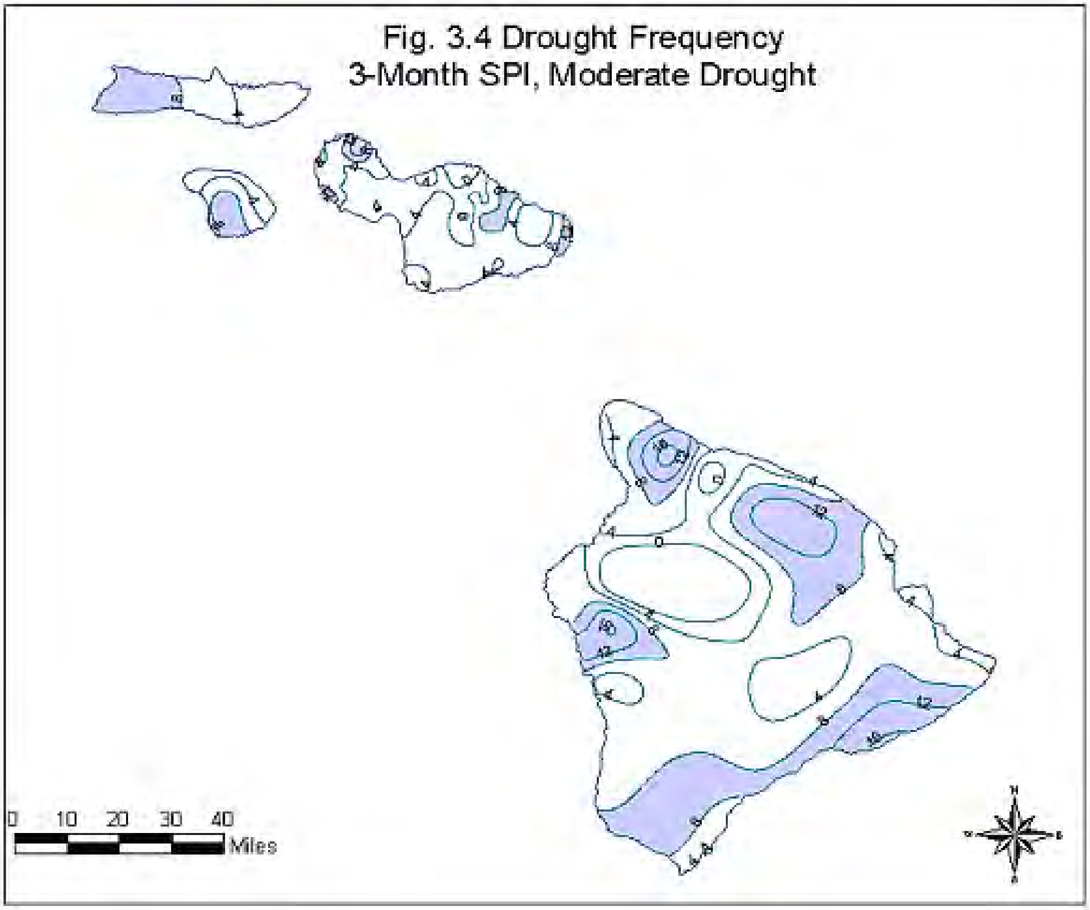


Figure 3.5 Drought Frequency - 3-Month SPI, Moderate Drought (City and County of Honolulu and Kauai County)

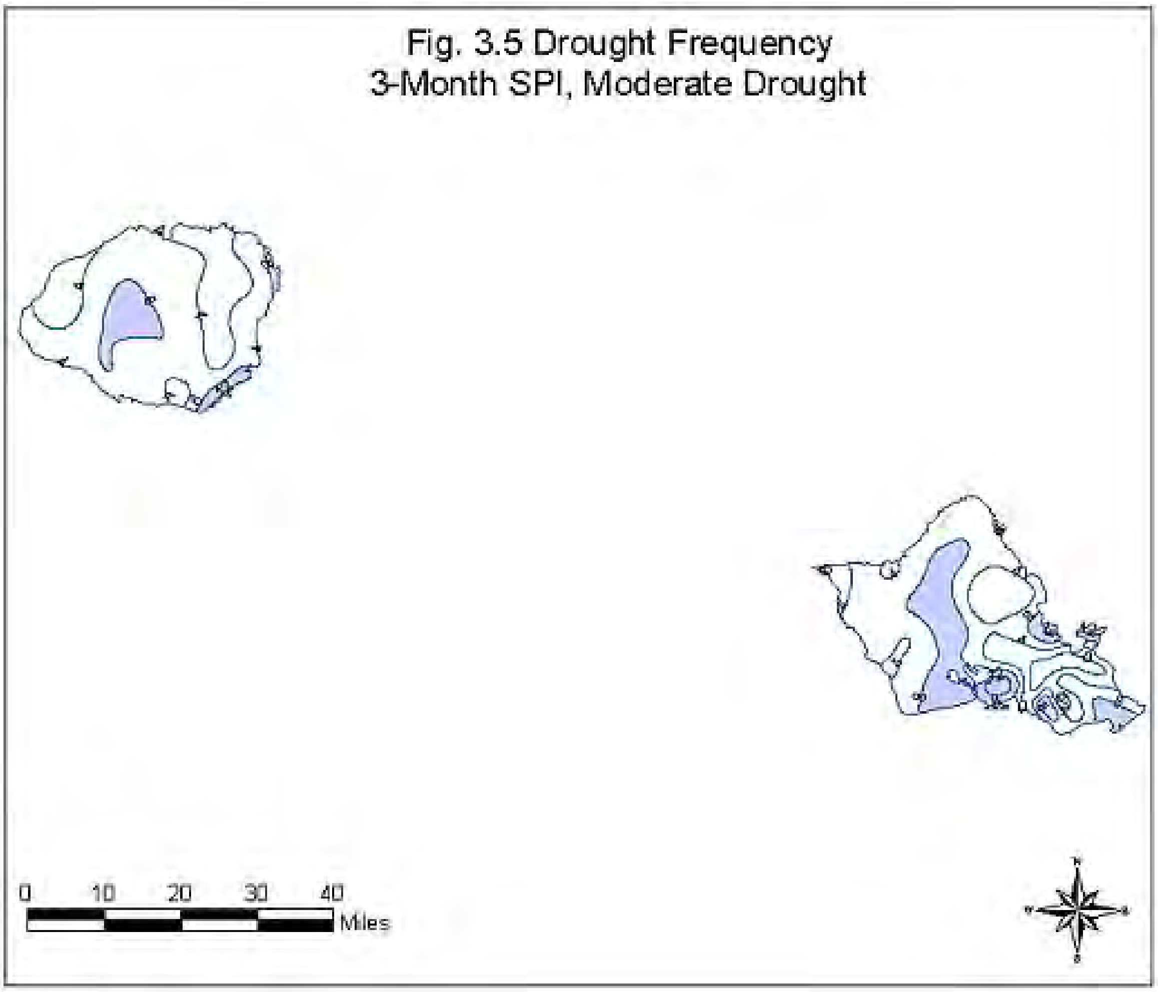


Figure 3.6 Drought Frequency - 3-Month SPI, Severe Drought (Hawaii and Maui County)

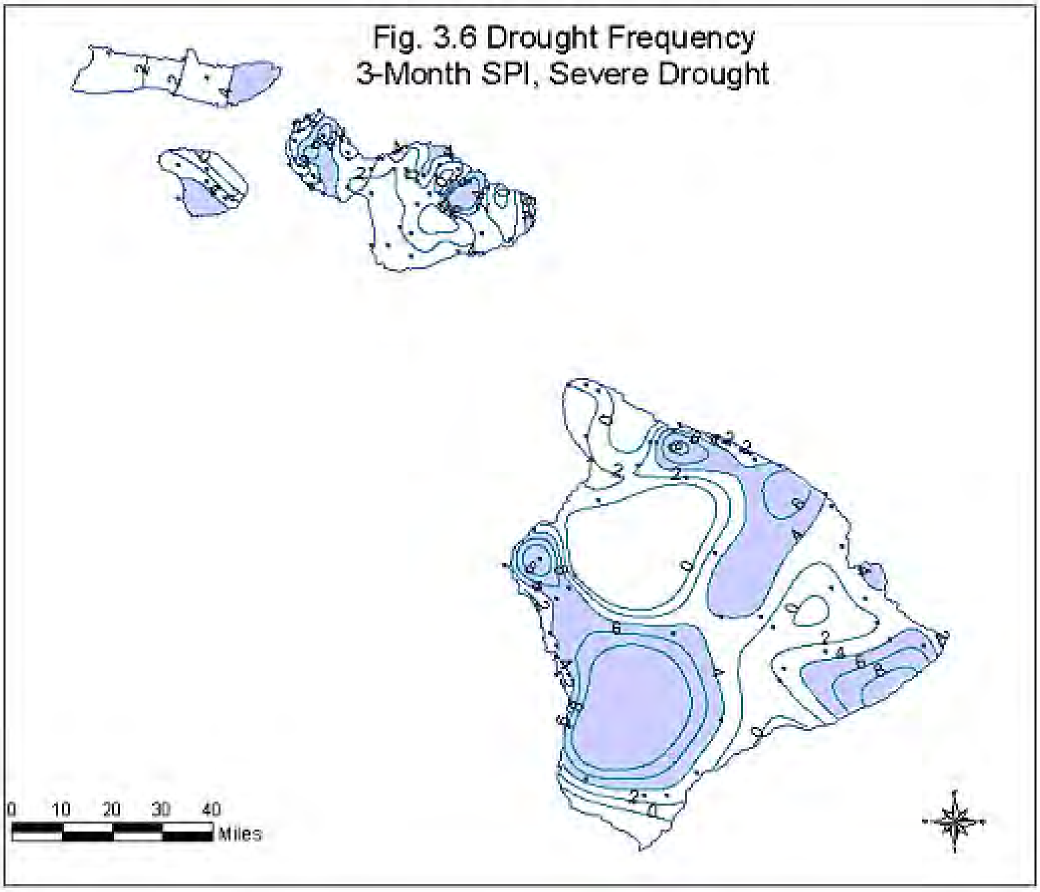


Figure 3.7 Drought Frequency - 3-Month SPI, Severe Drought (City and County of Honolulu and Kauai County)

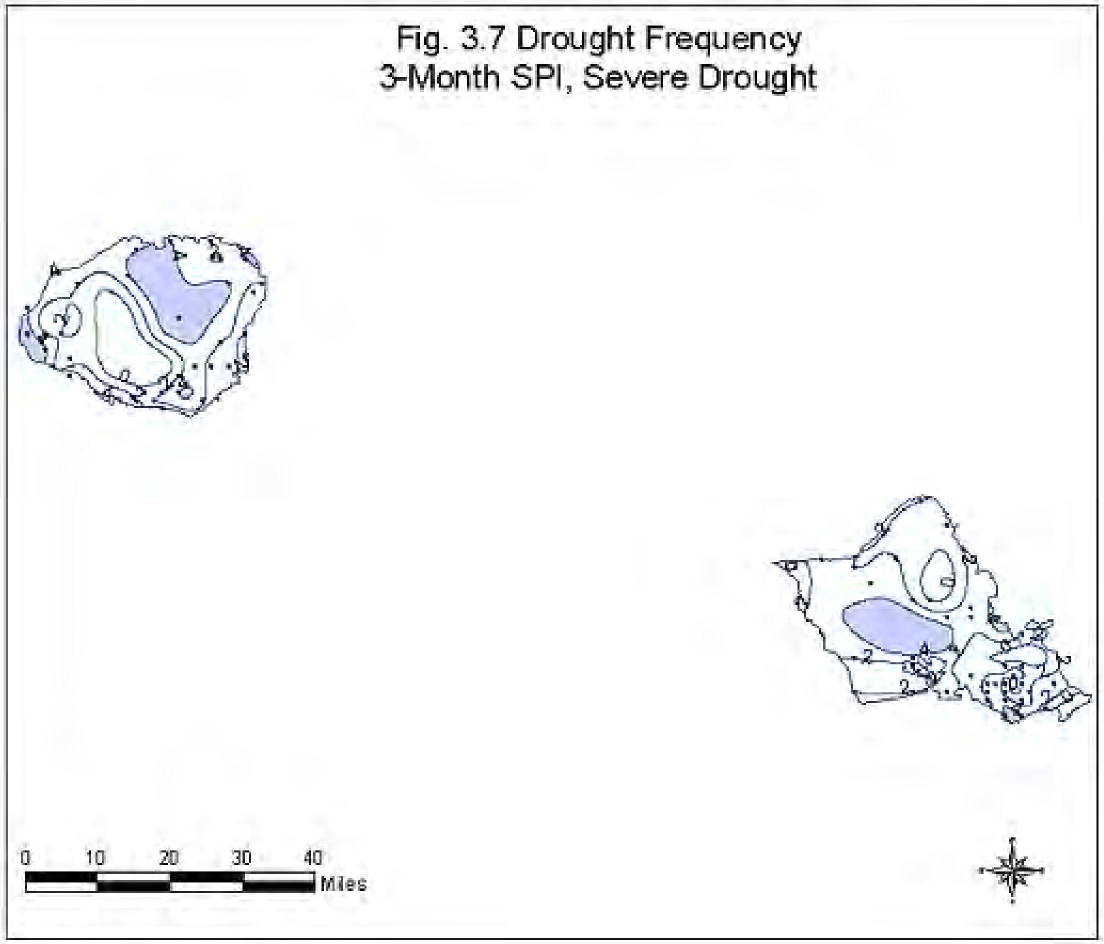


Figure 3.8 Drought Frequency - 12-Month SPI, Moderate Drought (Hawaii and Maui County)

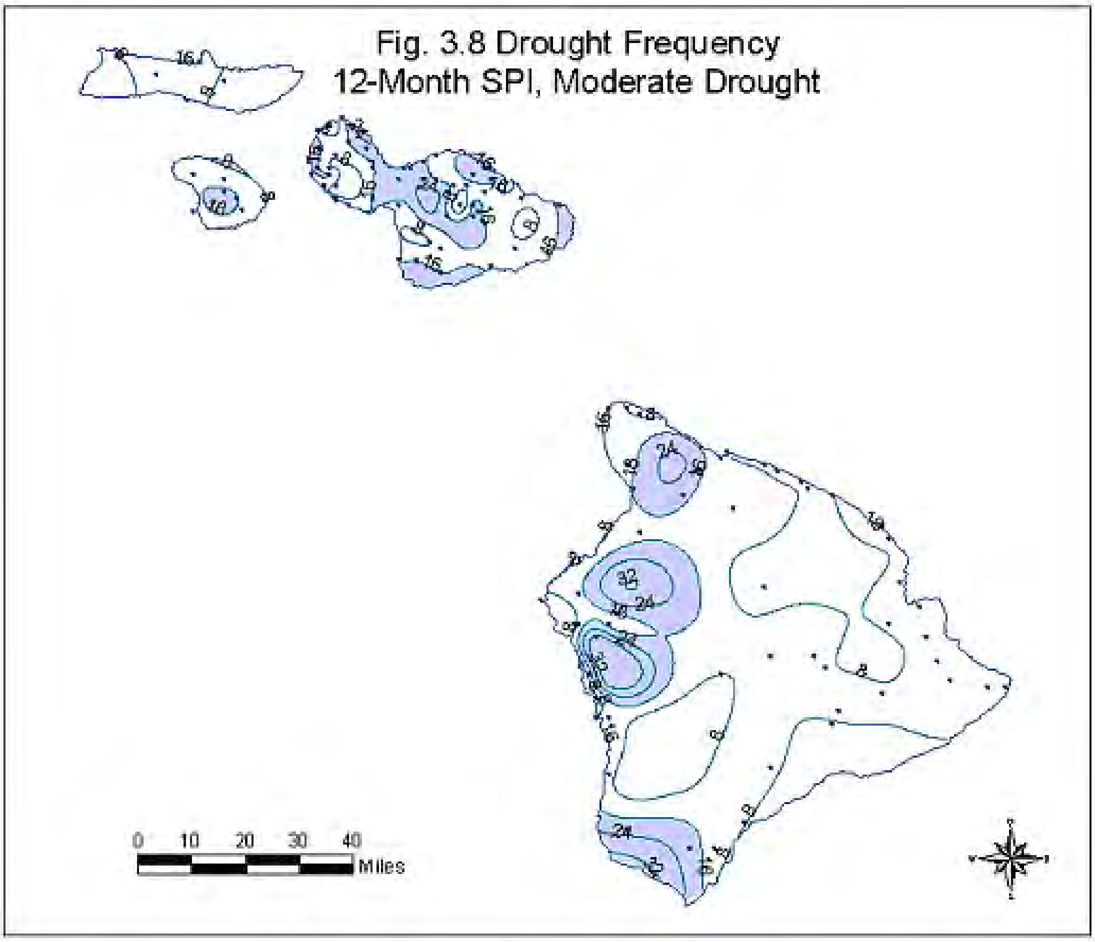


Figure 3.9 Drought Frequency - 12-Month SPI, Moderate Drought (City and County of Honolulu and Kauai County)

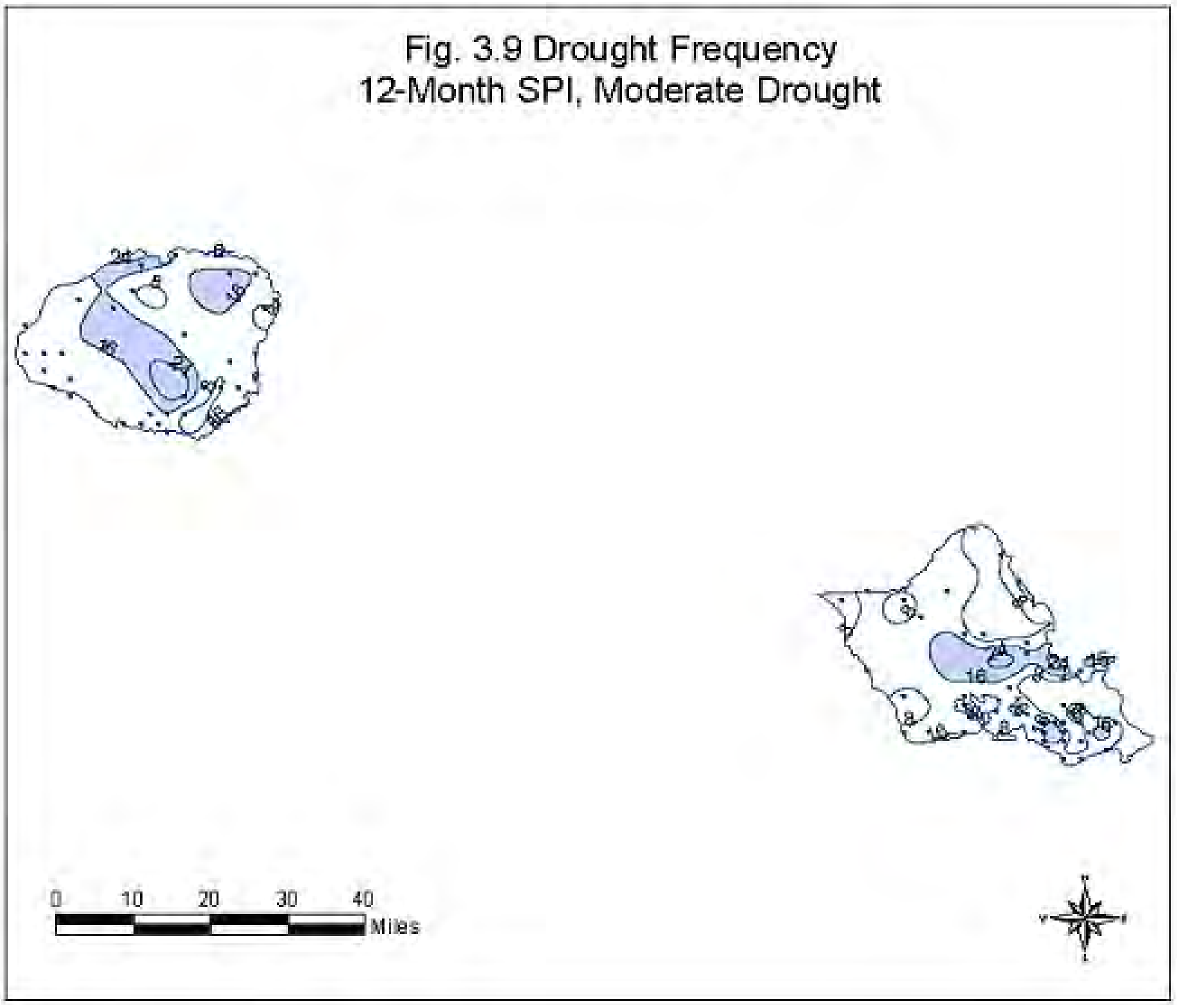


Figure 3.10 Drought Frequency - 12-Month SPI, Severe Drought (Hawaii and Maui County)

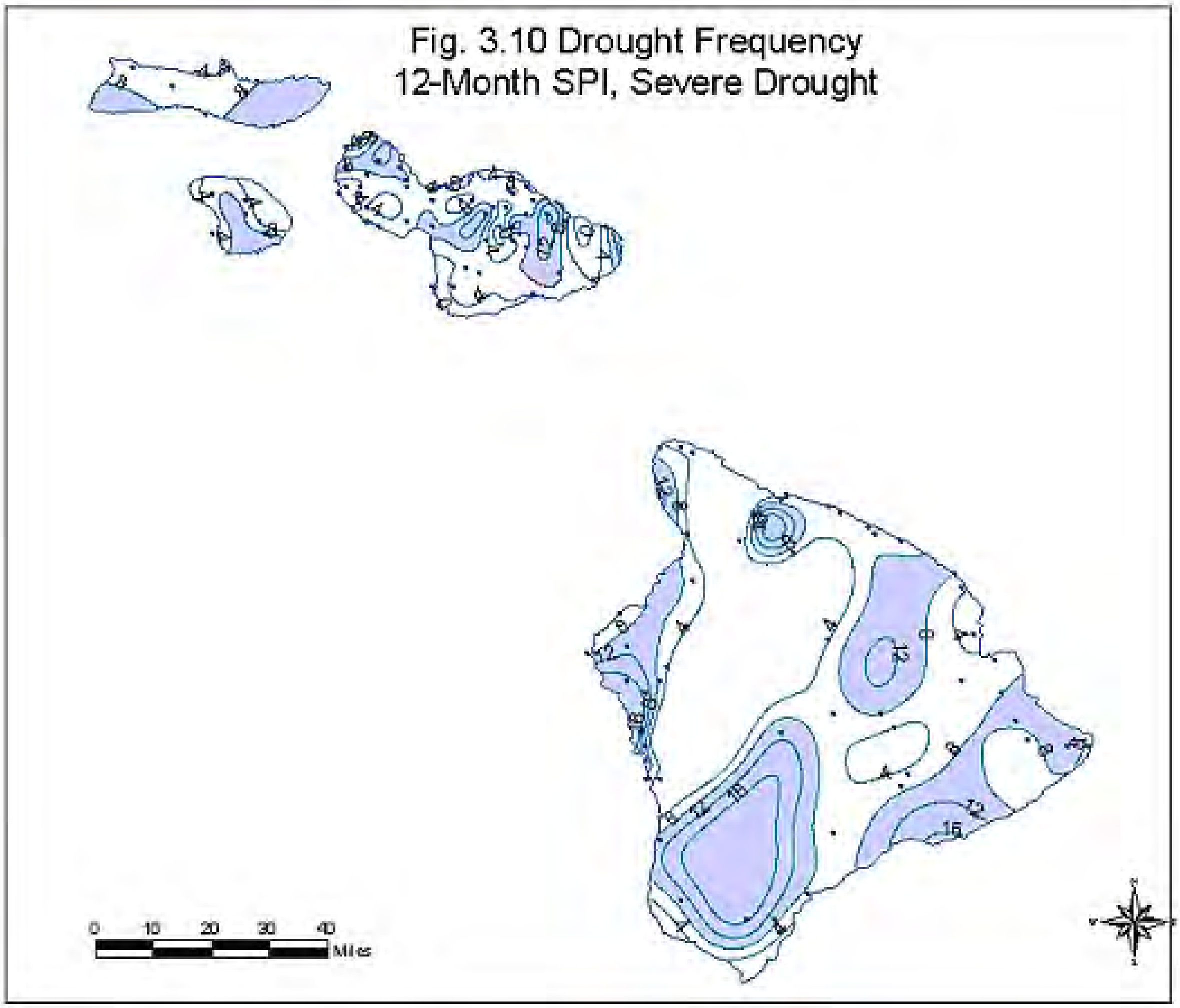


Figure 3.11 Drought Frequency - 12-Month SPI, Severe Drought (City and County of Honolulu and Kauai County)

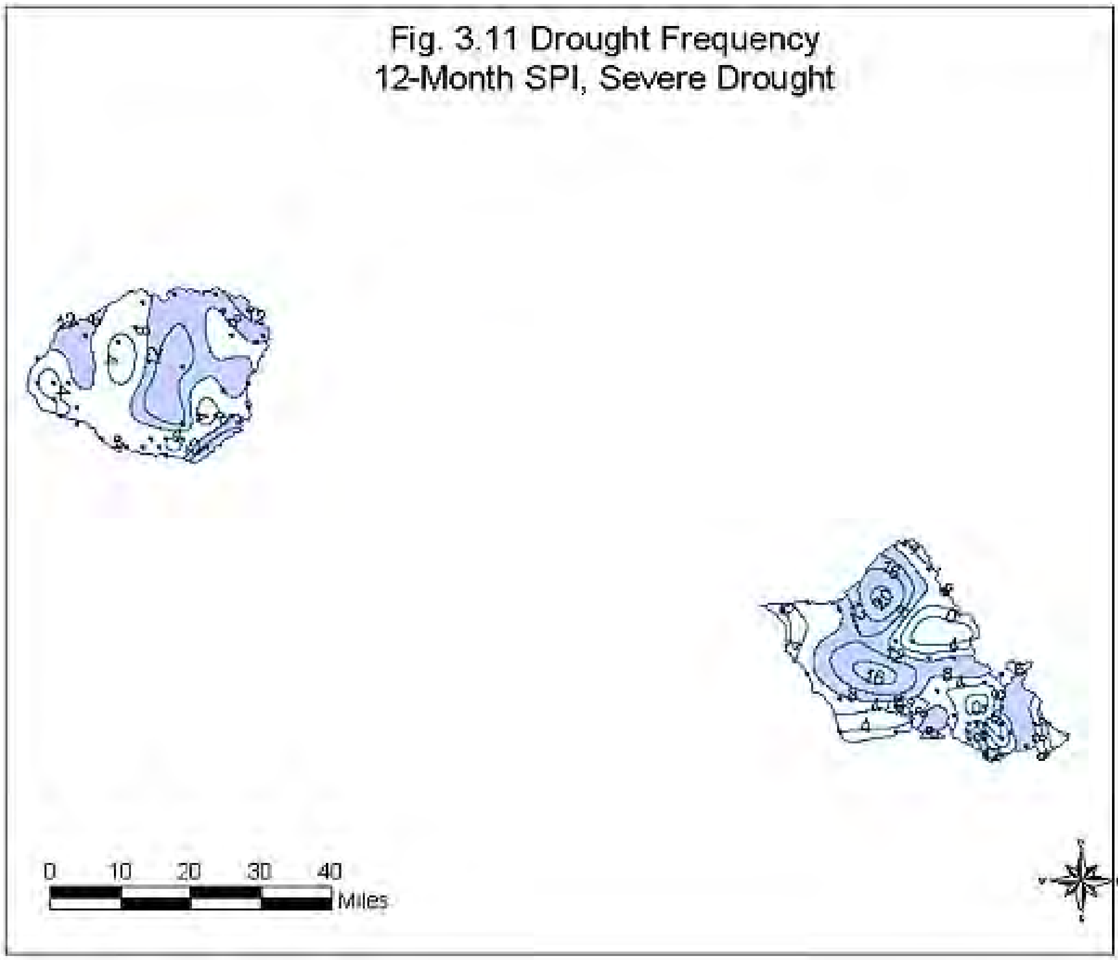


Figure 3.12 Locations of Rain Gages During 1942 - 1971

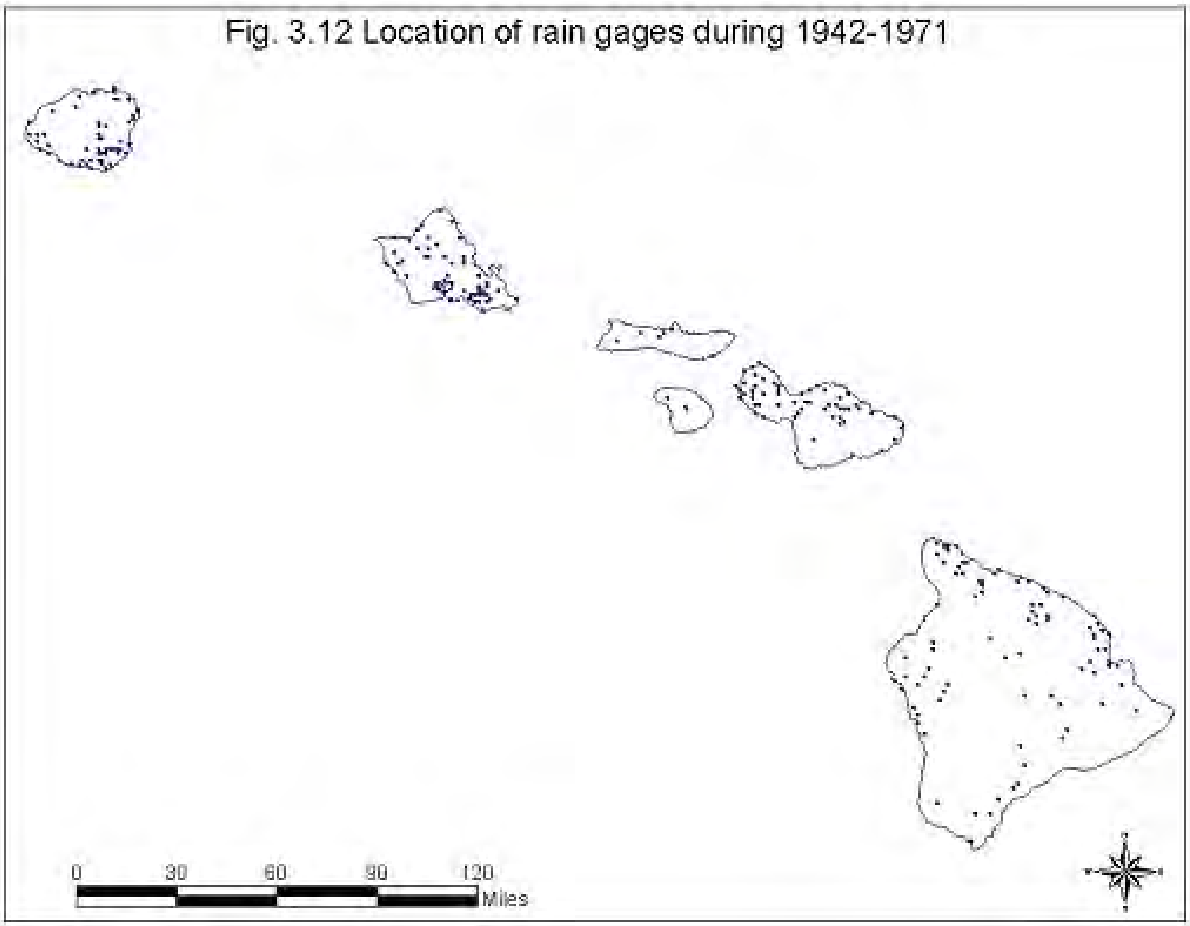
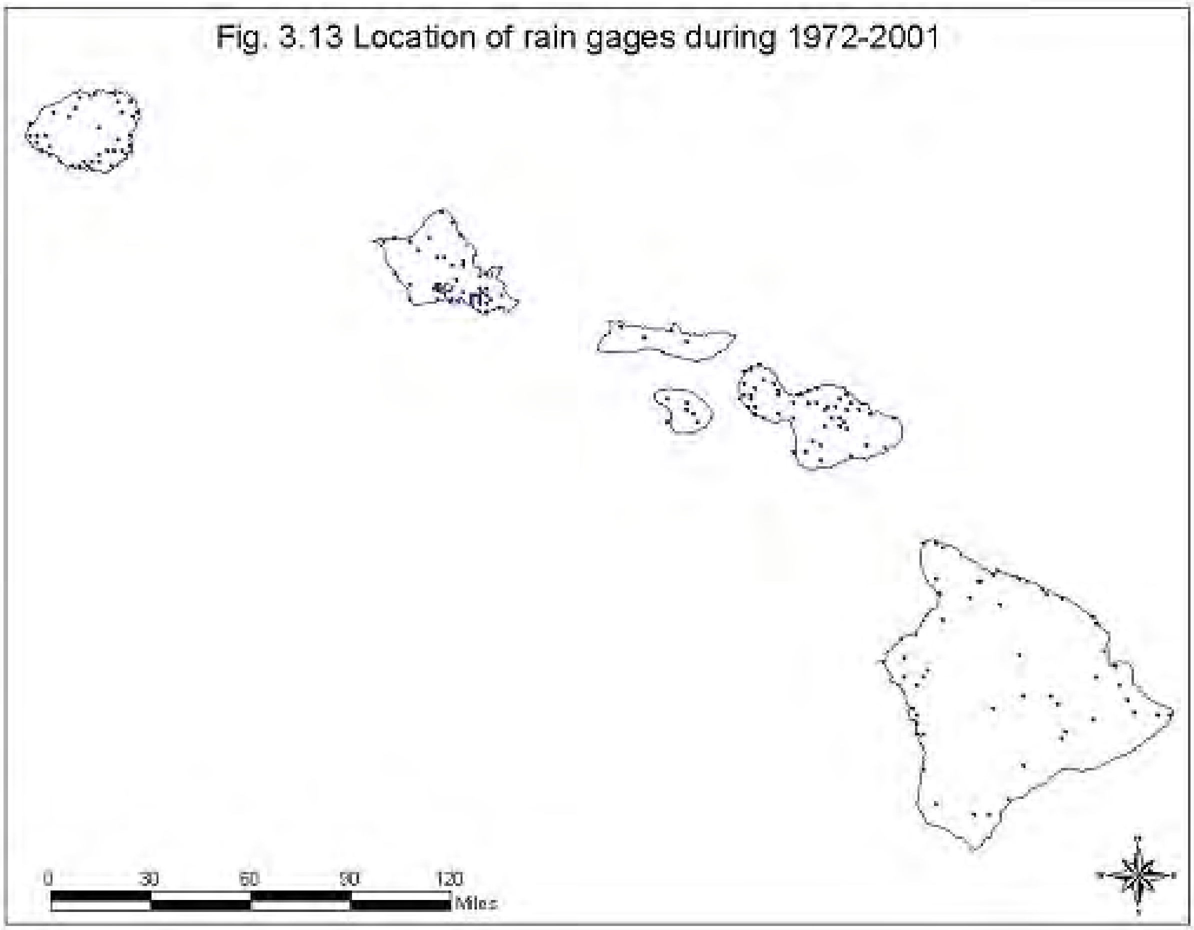


Figure 3.13 Locations of Rain Gages During 1972 - 2001



4. STATEWIDE VULNERABILITY ANALYSIS

4.1 BACKGROUND

4.1.1 UNDERSTANDING DROUGHT VULNERABILITY

According to the Western Drought Coordination Council drought vulnerability is the "characteristics of populations, activities, or the environment that make them susceptible to the effects of drought. The degree of vulnerability depends on the environmental and social characteristics of the region and is measured by the ability to anticipate, cope with, resist, and recover from drought. (Knutson et. al., 1998)

Hawaii's vulnerability to drought is the product of numerous interrelated factors such as population growth and shifts, urbanization, demographic characteristics, water use trends, social behavior, and environmental susceptibilities. These factors are continually changing, and society's vulnerability to drought may rise or fall in accordance with these changes. Vulnerability is most common conceptualized in the drought discourse as the characteristics of a population, land use activities, and/or the environment that make the population susceptible to the effects of a drought. The degree to which a population is vulnerable then hinges on the ability to anticipate, to deal with, resist, and recover from the drought. For example, a public water system with only one well that has a relatively low yield and minimal water storage is more vulnerable to drought conditions. Hence, awareness of the various facets of vulnerability and what aspects are more malleable through policy and other mechanisms is central to formulating mitigation strategies. The analysis in this study was designed around these various tenets.

The project focused on the sectors that are likely to be impacted during a drought, the impacts of which would be significantly detrimental to human, economic, and environment health, and which could be ameliorated through mitigation measures. The evaluation of Hawaii's vulnerability to drought was thus examined within three "sectors": Water Supply, Agriculture and Commerce, and Environment, Public Health and Safety. This study is vital in assessing the magnitude of drought vulnerability in relation to specific communities, and to adequately manage the impacts of ongoing and/or future droughts.

4.1.2 APPLICATION OF GEOGRAPHIC INFORMATION SYSTEMS

A GIS or Geographic Information System is a system of computer hardware, software, and data for capturing, storing, checking, integrating, manipulating, analyzing and displaying data related to positions on the Earth's surface or in other words, spatial data. Spatial data is data related to the space around us; data related to a location. Geographic information typically consists of data about time, space, and some attribute. Data are collected about a phenomenon and where it occurs at a particular time or how a phenomenon in a certain location changes over time. The roots of geographic information systems begin with maps. These might be represented as several different layers where each layer holds data about a particular kind of feature. GIS layers can be found in several data structure formats: points, lines, polygons, raster grids, and raster images. Databases offer the ability to amass large quantities of data. GIS offers the ability to integrate many different types of data through the use of common geography. Each feature is linked to a position on the graphical image of a map. Layers of data are organized to be studied and to perform statistical or spatial analysis. Geographic information systems (GISs) allow users to analyze geographic phenomena within areas of interest, thus leading to a better understanding of relationships and to provide a helpful tool in decision-making. Simply put, a GIS combines layers of information about a place to give you a better understanding of that place. What layers of information you combine depends on your purpose.

Utilizing the strength and capabilities of GIS, this analysis used methods to overlay, query, highlight, and select layers that were determined as being critical to the examination of the potential vulnerability of the drought impact sectors. The analysis consisted of deriving new maps of the likely occurrence or magnitude of a particular phenomenon based on the established relationship between the existing maps layers.

One must understand that there are inherent uncertainties when working with data layers derived from many sources. Metadata does not always account for the numerous inconsistencies and accuracy issues that can arise. This is especially true when the best available datasets are themselves based on approximations. Neglecting those inherent uncertainties in spatial representations may result in misinterpretations even among otherwise informed and well-intentioned individuals. There are several sources of uncertainty contributing to the quality of spatial data within a GIS: imperfections (e.g., inaccuracy and imprecision) and effects of discretization. An example for discretization in the thematic domain is the chosen number of classes to represent a spatial phenomenon (i.e., rainfall or air temperature).

4.2 PURPOSE AND METHODOLOGY

The purpose of the Drought Vulnerability Analysis component of this study was to identify areas vulnerable to drought within the sectors of water supply, agriculture and commerce, and public health and safety, and to spatially represent the location and extents in the form of maps. This sector based vulnerability information was then overlaid with the results of the drought frequency analysis conducted in section three of the report, to examine the areas across the state, and within each sector, that may be subject to drought risk. The Drought Risk Assessment is discussed in Section 5 of this report.

4.3 VULNERABILITY ANALYSIS

4.3.1 WATER SUPPLY SECTOR

4.3.1.1 DESCRIPTION OF SECTOR

According to the Environmental Protection Agency (EPA), 1,292,059 people were served by Hawaii’s public water system in 2002 (EPA, 2002). A public water system (PWS) is defined by the EPA as a system that provides water to the public for human consumption through pipes or other constructed conveyances. To be considered a PWS, the system must support at least fifteen service connections or regularly serve at least twenty-five individuals (EPA, 1998). Across the four counties of Hawaii, there are 58 public water systems administered by the County Water Departments, 62 private water systems, and 13 military systems. Most of the systems are supplied by groundwater sources, but there are also 11 surface water systems, and 4 catchment water systems that are considered public water systems by the Department of Health. In 2001, there were a total of 242,092 service connections, covering approximately 367,869 acres statewide (Table 4.1). Of those service connections, the City and County of Honolulu had a total of 157,429 service connections by the Honolulu Board of Water Supply, servicing

123,963.78 acres. This calculates to approximately 1.27 service connections per acre. Hawaii County, which only had a total of 35,962 total service connections, but had much larger service area coverage (178,008.831acres), had the lowest service rate of 0.20 services per acre. However, given the spatial extent of the population distribution and the size of the county, the service rate is not necessarily revealing of any service shortcomings.

Table 4.1 Public Water Services by County

Geographic Area	Number of Services Connections(2001)	Water Service Acreage	Services/Acreage	Service Area Pop.
City and County of Honolulu	157,429	123,963.781	1.27	974,653
Hawaii County	35,962	178,008.831	0.20	122,235
Kauai County	18,287	34,642.932	0.53	64,588
Maui County	29,750	75,022.914	0.39	135,892
State Total	242,092	367,860.65	0.66	1,297,368

4.3.1.2 WORKING ASSUMPTIONS

In the analysis of Hawaii's water supply sector's vulnerability to drought, both an operational and conceptual approach was taken to determine the degree of vulnerability.   From an operational drought standpoint, annual precipitation distribution totals were classified as either being High, Medium, or Low and represented as a contour based on a third (tercile) of the total annual rainfall figures. This approach was done as a means to not only provide visual clarity and ease of readability in the final map, but also as a means of converting a quantitative range of values into a more qualitative and accessible form of rainfall totals.

Based on these terciles, areas of low rainfall could readily be identified as vulnerable to meteorological drought. However, it is important to note that there are multiple perspectives on whether low rainfall areas or high rainfall areas are more vulnerable to drought, especially when vulnerability refers to so many impact sectors. For the sake of this study it was a key operational question: would an area experiencing normally high precipitation be much more vulnerable because of the shock of receiving lower precipitation, or were areas already receiving low rainfall totals more vulnerable due to a sustained relative lack of precipitation. Given the impact sectors covered by the study and the fact that areas that typically receive greater amounts of precipitation would have greater storage yields, low rainfall areas are considered more vulnerable.

The conceptual approach in the project analysis involved several assumptions regarding the water supply system in general. The public water supply in Hawaii is provided by municipal, military, and private systems across the state. Delineation of the service areas, except for private catchment systems, was used as a means of determining the extent of Hawaii's potable public water system. Populated areas outside of these delineated boundaries were assumed to be on a private water catchment system, and hence more dependent on regular precipitation than areas serviced by public water supplied from groundwater or surface water sources. Areas that are serviced by non-integrated water systems, whether from groundwater or surface water, are also considered more vulnerable to drought than areas serviced by an integrated system. This is based on the redundancy or reliability of integrated systems able to provide water from nondiscrete sources. Furthermore, if drought conditions are geographically specific, an integrated system would still be capable of providing water to those affected areas from other sources.

Given our primary assumption that integrated water systems are more reliable, and thus less vulnerable, than catchment systems, it is important to acknowledge the differing vulnerability among integrated systems. Integrated systems that are supplied by groundwater are considered to be less vulnerable than integrated systems that are supplied by surface water sources. The rationale is based on surface water system vulnerability to hydrological drought. There are significant surface water supplied systems throughout the State that complicate our vulnerability analysis. The Hawaii County populations in South Kohala and Pahala are served by surface water systems. In Maui County, on Maui the Makawao, Upper Kula, Lower Kula, and Lahaina populations are served by surface water systems. Likewise, on Molokai the Kaalakoi and Maunaloa populations are supplied by surface water systems.

4.3.1.3 METHODOLOGY

Working off of the assumptions stated in the previous section, the study utilized a GIS-based suitability analysis. The analysis, which is built on the assumption that areas of lower annual median rainfall are more vulnerable to drought, is an attempt to identify especially vulnerable centers of high population density that lack public water access situated within these areas. Given that human vulnerability is an important aspect of this sector and that there is a need to provide a focus to the analysis, population density was not simply derived from land area and population totals. Census population data taken at the block level was first isolated to only include census blocks that had some population, hence focusing on the human vulnerability component. Once these "zero populated" areas were removed, population density was calculated for each census block. Population density is the term that describes the number of individuals occupying an area in relation to the size of that area. The population density is derived by dividing the number of people by the area they occupy. Hence, the population density figure is measured as the number of people per square mile. Population density was used instead of total population because it is a better indicator to measure the pressures on the environment including: exploitation of natural resources, such as water and land; contamination of a city and its surroundings; and air pollution by traffic and manufacturing industries.

The population data was then re-classed using natural breaks instead of quantiles because quantile classification methods are not suited for population distributions that are disproportionate. The natural break method identifies breakpoints between classes using a statistical formula (Jenk's optimization). This method is rather complex, but basically the Jenk's method minimizes the sum of the variance within each of the classes. Natural Breaks finds groupings and patterns inherent in the data sample. The Jenk's formula guarantees an optimal solution for grouping similar values together. It can also be used to determine the appropriate number of classes. The goodness of absolute deviation or variance fit can be calculated for different numbers of classes (Coulson, 1987).

After classifying using the natural break method, the lowest densely populated blocks were removed. This class was removed because there lacked a significant density of the population at risk in terms of water supply in these areas. After the low end of the population density distribution curve is removed, the data becomes more linearly distributed and the quantile method can then be used to produce the most appropriate classification of the data. Overlaying the layers of the median annual rainfall terciles, the population density quantiles, and the public water service areas along with reference themes produces a map where areas subject to low rainfall and high population density outside the public water service areas can be highlighted as the areas most vulnerable to drought within the water supply impact sector.

4.3.1.4 DATA SOURCES

The data utilized in this part of the analysis was obtained through several organizations with GIS and non-GIS capability throughout the State of Hawaii and at the Federal Government level. In this water supply vulnerability analysis, and the other impact sector analyses, there were two types of GIS data layers that were considered. For the purposes of this report, data layers will be referred to as either critical layers or reference layers. The critical layers are GIS layers that are critical in the overall analysis of determining vulnerability, and the reference layers include those used specifically to provide better overall locational reference information on where the vulnerability may be occurring or other reference information to improve the ability to understand the situation.

For this particular analysis regarding the vulnerability of the water supply sector, the critical layers include:
1) Public and private water service areas;
2) Population demographic information; and
3) Rainfall terciles.

The public and private water service areas were obtained from county water departments, military water services, and other private water purveyors. It should be noted that the municipal service areas are conservative and were created for planning purposes only. Hence they are limited to areas that may have appropriate planning and zoning approvals in place. The municipal service areas should include: 1) all existing service areas, including infill areas; 2) areas which are planned and zoned for future urban development and for which developers are required to provide water supply infrastructure; and 3) approved agriculture subdivisions for which developers are required to provide water supply infrastructure. The military bases and properties with water supply services are also represented in polygon data structures and include all existing water service areas where the water source is under the jurisdiction of the U.S. Armed Forces. Private water service areas include areas where water sources are under the direct control of a private corporation or entity. These areas were obtained directly from the private entity. There are some limitations in the water service area data and the analysis because it assumes that all the service areas have been accounted for in either paper map format or in GIS data format. For example, in Hawaii County there are several areas along the Kona Coast, i.e., Keahole Airport and the surrounding urban/industrial areas, which are not covered by existing map data in either paper or GIS formats, but more than likely should be included as being serviced by a public water source. Hence, to obtain a full accounting of the vulnerability to the water supply sector may require future detailed investigation into the spatial extent of current public water supply services.

The population demographic information from the year 2000 Census was obtained at the Census Block Level from the United States Census Bureau. Census blocks are the smallest division of Census Population Tabulation Areas and are bounded on all sides by visible features, such as streets, roads, streams, and railroad tracks, and by invisible boundaries, such as city, town, township, and county limits, property lines, and short, imaginary extensions of streets and roads. However, census blocks in sparsely settled areas may contain many square miles of territory. The minimum size of a census block is 30,000 square feet (0.69 acre) for polygons bounded entirely by roads, or 40,000 square feet (0.92 acres) for other polygons.[4] There is no maximum size for a census block. The U.S. Census Bureau also uses other population tabulation areas, namely the census tract and block group (U.S. Census Bureau, 1994). These areas were considered too large to be useful in this analysis.

The rainfall terciles were created using GIS interpolation functions to convert rainfall isohyets into a continuous raster or grid surface. The original isohyet dataset was obtained from State of Hawaii's Department of Business, Economic Development and Tourism (DBEDT), Office of State Planning's GIS program. The isohyet data is described as median annual rainfall in millimeters and inches. The raster or grid is defined as a geographic data model representing information as an array of equally sized square cells arranged in rows and columns. Each grid cell is referenced by its geographic x,y location. Conversion to a raster grid format provided a data structure that allows grid based algebra analysis or the conversion of the rainfall data into a polygon feature dataset to combine and overlay on the other datasets to perform a suitability analysis.

Reference data layers included the following:
1) Major roads; and
2) State Land Use Districts.

As stated previously, reference layers were only used to highlight a particular locational feature or provide other visually meaningful interpretation information. The major road layer was obtained from the DBEDT, Office of State Planning's GIS program. The roads used were originally from the U.S. Geological Survey's Digital Line Graph (DLG) roads produced in 1983. The major roads provided visual reference points on the maps. The State Land Use Districts boundaries were compiled by the State Land Use Commission using the State of Hawaii's Geographic Information System (GIS). The State Land Use Districts depicted in these files are not official and are for reference purposes only. These land uses divisions are not comprehensive or inclusive, hence a particular land use district designation does not imply that all land use activity in the area is as the district boundary states.

The land uses are classified based on a land use boundary code (ludcode) of either:
1) A – Agricultural Land Use District;
2) C – Conservation Land Use District;
3) R – Rural Land Use District; or
4) U - Urban Land Use District.

The land use district boundary provides the map interpreter a "big picture" view of what may be potentially at risk from drought based on the broad categories provided by the State Land Use Districts.

4.3.1.5 VULNERABILITY MAPS AND DISCUSSION OF RESULTS

The final maps and findings for the vulnerability analysis of the public water supply sector can be seen on Figure 4.1 to Figure 4.4. Figure 4.1, "Drought Vulnerability Areas, Water Supply Sector, County of Hawaii," shows that over 50 percent of the Big Island of Hawaii is

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[4] U.S. Census Bureau, 2000. Geographic Area Reference Manual, Chapter 11.
http://www.census.gov/geo/www/GARM/GARMcont.pdf

classified in the lowest third rainfall tercile, and service areas are lacking in some areas with concentrated populations along the Kona Coast and in Pahoa. The vulnerable areas on the Big Island of Hawaii that fit the criteria based on the assumptions of low rainfall, high population, and locations outside the service area are the areas in South Kohala and South Kona. To a lesser degree, high population areas within the Pahoa region are within the medium tercile of annual rainfall and are not within the public water service areas.

Within Maui County, as shown on Figure 4.2, the most apparent area of high vulnerability within the water supply sector is on the island of Lanai. However, it is important to note that in Kula and Makawao the water system is served by surface sources in East Maui, and thus are vulnerable despite service coverage. Reinforcing the premise that service coverage does not always eliminate vulnerability, greater than 50 percent of both Maui and Molokai are in the low tercile of median annual rainfall and have the largest density of population within the respective islands, hence increasing the vulnerability of the those areas to drought even though they are serviced by the public water supply system.

The City and County of Honolulu has the most extensive public water supply system. According to the Honolulu Board of Water Supply, approximately 92 percent of Oahu's water comes from groundwater. The integrated municipal water system within the City and County of Honolulu, draws water from where it is plentiful and pumps it to where people live through its 1,842 miles of pipelines. Because of this flexibility, the Board is able to move water from one district to another, which is particularly helpful during emergencies. Based on Figure 4.3, one can see that the majority of the City and County of Honolulu is within the public water supply system; this includes the areas of high populations within the low tercile rainfall regions along the Ewa Plain and the Waianae Coast.

Within Kauai County, as displayed in Figure 4.4, approximately over 75% of the island is within the low rainfall tercile, unfortunately all the population areas fall within those areas, but they are all serviced by the public water supply system. From this, one can infer that the population may not be as susceptible to meteorological drought, but more susceptible to hydrological drought.

4.3.1.6 CAVEATS AND DATA LIMITATIONS/DEFICIENCIES

It must be taken into consideration that the resulting maps of this analysis are very general, and are subject to many interpretations. Because of this general nature, they should only be used for planning purposes and not taken as hard, set definitions of vulnerability.

Data limitations in regards to the original data used in this analysis are primarily due to lack of data standards between counties, and the general lack of data itself. In terms of the water service areas, each county has created its own layer, and as such have different standards regarding the layers overall utility. Some counties water service areas are tied closely to the parcel/tax map key system (TMK), hence providing a greater idea of total public water service area coverage. While others may not be closely tied to this system, hence just providing an approximation of overall coverage, and still others may not have had a service area system in place, for which an estimation had to be made based off of the water-main line coverage. To provide a better means of determining public water service area and the vulnerability, there should be more coordination between each county's water departments on a standard service area methodology, preferably based on the TMK system, because that layer is closely tied into land use activity on each parcel, as well as other pertinent information regarding the parcels. For those large parcels that are not fully serviced across the entire width of the parcel, some form of percentage factor could be utilized to determine coverage. Additionally, a few privately owned water systems are not represented since they were not able to provide data in time to be included in this report. These systems will be shown in future revisions of this report.

In some areas, the tercile division of rainfall may be too coarse. For example, on the island of Hawaii, the lowest rainfall designation includes all areas with rainfall less than approximately 100 inches annually. This results in the clustering of areas receiving 20 inches of annual rainfall with areas receiving 100 inches of annual rainfall. Future refinement of the vulnerability analysis should address this by increasing the number of annual rainfall divisions, or tailoring rainfall divisions appropriately for each sector.

Adding information regarding groundwater or source water yield and average daily demand based on land use activity per acre, along with the public water service area can greatly improve the determination of where there may be vulnerabilities. Also, because census population data does not necessarily reflect the actual demand for water, but rather a proxy, this added data with the census population would provide greater clarity on vulnerability to the resulting analysis.

4.3.2 AGRICULTURE AND COMMERCE SECTOR

4.3.2.1 DESCRIPTION OF SECTOR

The history of agriculture in Hawaii spans from prior to1778 when the first foreigners arrived on the islands. Several key points in history mark the beginnings of Hawaii's plantation and ranching agriculture activities. The Parker Ranch had its beginnings in 1809, when John Palmer Parker began domesticating wild cattle and horses on the Big Island of Hawaii. The first successful sugarcane plantation began in 1835 at Koloa, Kauai. The first documented plantings of pineapple in Hawaii took place in 1813, and in 1882 the pineapple was commercially canned in Kona. For nearly a century, agriculture was the leading economic activity in the State of Hawaii. It provided Hawaii its major source of employment, tax revenues, and new capital through exports of raw sugar and other farm products. The islands of Oahu and Hawaii saw their final sugarcane harvests in 1996. Today, sugarcane is grown on about 70,000 acres on Kauai and Maui yielding some 340,000 tons of raw sugar. Agriculture is still an important part of Hawaii's economic mix and sugar is still the second largest single crop grown in value with the largest acreage.

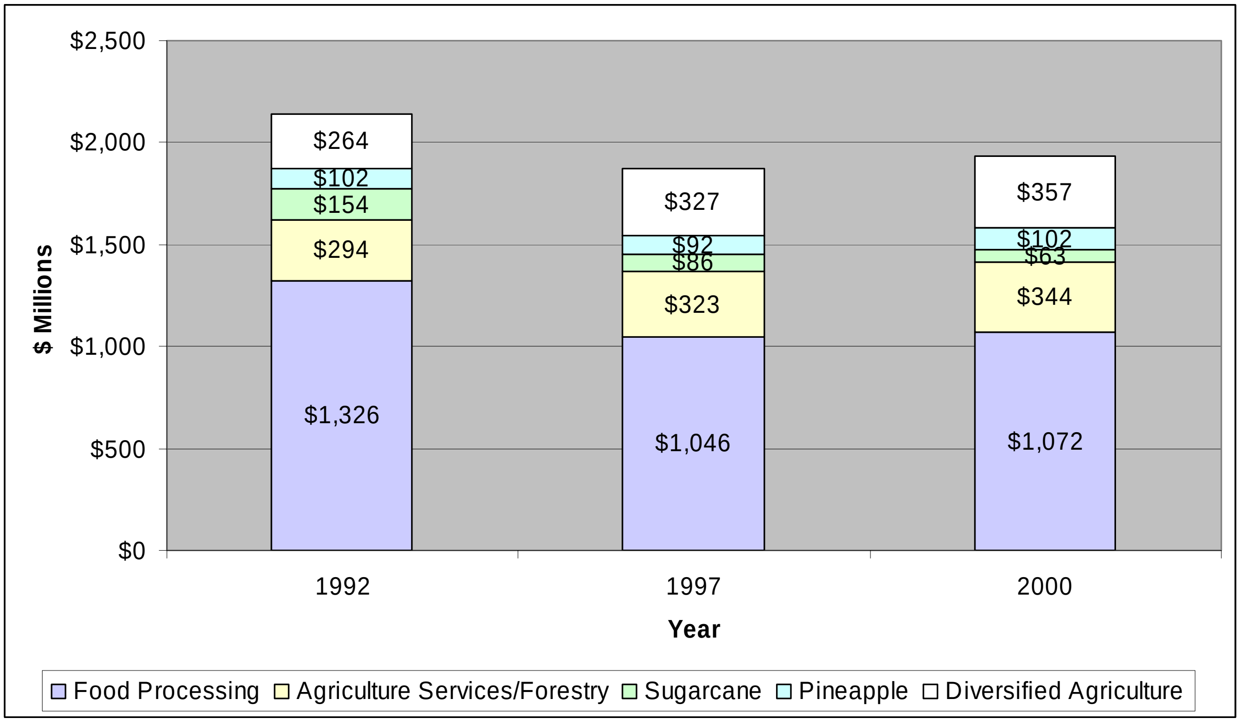
How much of a role does agriculture play in Hawaii's economy? Sales value is the most common measure of economic activities. It includes the out-the-door, or what is referred to as farm-gate value that is routinely reported by the Hawaii Department of Agriculture. Total agriculture sales (farm production, agricultural service, forestry and fisheries, and food processing) decreased from $2.14 billion in 1992 to $1.87 billion in 1997, but rebounded to $1.94 billion in 2000. Pineapple sales value remained stable at $102 million after a slight decline in 1997. The continual decrease in sugarcane sales value is largely offset by the tremendous growth in sales value of diversified agriculture (including seed crops, coffee, macadamia nuts, fruits, vegetables, flowers, and nursery products), which increased at an annual rate of 3.8% between 1992 and 2000. Reflecting this trend, the sales value of diversified agriculture jumped from just over 50% of total farm production in 1992 to almost 70% in 2000. Diversified agriculture posted record high sales of $357 million in 2000.[5] In 1997 the estimated total contribution of Hawaii's agriculture in terms of value added was $4.72 billion and employment was 114,431 jobs; these correspond to 12.3% of Hawaii's total value added and 15.4% of state employment.[6] Based on Chart 4.1, total agriculture related sales in Hawaii have decreased by a total of $194 million dollars between 1992 and 2000, but diversified agriculture sales have increased by $93 million dollars over the same period.

Table 4.2, illustrates the total number of land acreage, number of crop farms, and number of sales in $1000s of dollars for the year 2001 for each of the four counties. This table includes both diversified agriculture and land intensive crop agriculture. Based on these figures, Maui County has the most land being used by agriculture (45,700 acres), with 9,100 acres in pineapple and 35,400 acres in sugarcane. Also, based on the figures provided by the DBEDT, Kauai County has 16,500 acres and the City and County of Honolulu has a total of 15,900 acres in agriculture, most of which is in pineapple (11,000 acres). Hawaii County has the least acreage in agriculture (10,800 acres). Prior to 2000, not all sugarcane lands were irrigated. In 1999, there

[5] http://www.nass.usda.gov/hi/stats/stat-15.htm
[6] Dr. William Edmondson, ERS-USDA, provided the 1997 estimates, the most recent available. Quoted from http://www.nass.usda.gov/hi/stats/stat-15.htm

were a total of 4,922 acres that were non-irrigated, although much of the irrigated lands were supported by drip irrigation.[7]

Chart 4.1 Sales of the Agriculture Sector



Source: University of Hawaii, College of Tropical Agriculture and Human Resources (CTAHR)

As for livestock operations, or extensive agriculture, Hawaii County had 460 cattle operations in 2001, compared to 60 in Honolulu County (Table 4.3). According to the U.S. Department of Agriculture's National Agriculture Statistics, a livestock operation is defined as a place that has one or more head of the species on hand at any time during the year. It does not have to meet the definition of a farm. Hence, these figures do not necessarily represent only the big producers, which have acres of rangeland that are vulnerable to the drought conditions.

[7] State of Hawaii, Department of Business, Economic Development and Tourism. 2001. Hawaii State Data Book. http://www.hawaii.gov/dbedt/db01/19/191001.pdf

Table 4.2 Agriculture in Hawaii County (2001)

Acreage in Crop (1000 Acres)		# of Crop Farms	Value of Crop Sales($1000)
Hawaii County			
Sugarcane	-	-	-
Pineapple	1	6	2
Vegetables/Melons	1.9	270	17,742
Fruits excluding Pineapples	4.5	585	18,724
Coffee	3.4	675	13,175
Macadamia Nuts	NA	Withheld	Withheld
Taro	NA	60	443
Flowers & Nursery Products	NA	360	51,283
Maui County			
Sugarcane	35.4	1	44,900
Pineapple	9.1	2	27,115
Vegetables/Melons	1.2	100	10,125
Fruits excluding Pineapples	0.3	193	921
Coffee	Withheld	Withheld	Withheld
Macadamia Nuts	Withheld	Withheld	Withheld
Taro	NA	25	Withheld
Flowers & Nursery Products	NA	150	9,866
Honolulu County			
Sugarcane	-	-	-
Pineapple	11	2	62,222
Vegetables/Melons	3.4	160	32,601
Fruits excluding Pineapples	1.5	142	7,538
Coffee	Withheld	Withheld	Withheld
Macadamia Nuts	NA	Withheld	Withheld
Taro	NA	15	Withheld
Flowers & Nursery Products	NA	220	24,916
Kauai County			
Sugarcane	10.6	1	12,900
Pineapple	5	2	2
Vegetables/Melons	0.1	45	1,574
Fruits excluding Pineapples	0.8	139	3,007
Coffee	Withheld	Withheld	Withheld
Macadamia Nuts	Withheld	Withheld	Withheld
Taro	NA	70	2,258
Flowers & Nursery Products	NA	60	1,911

Table 4.3 Extensive Agriculture in Hawaii (2001)

# of Livestock Operations		Livestock Inventory (1000)	Value of Sales ($1,000)
Hawaii County			
Cattle	460	110.1	13,438
Hogs	70	4.4	456
Milk	28	2.6	Withheld
Chicken/Eggs	28	Withheld	Withheld
Maui County			
Cattle	170	19.7	2,438
Hogs	60	5.8	839
Milk	4	4	Withheld
Eggs	8	Withheld	Withheld
Honolulu County			
Cattle	60	9.4	604
Hogs	70	14.8	2,882
Milk	10	4.7	18,920
Eggs/Chickens	15	513	6,666
Kauai County			
Cattle	110	10.8	1,527
Hogs	30	2	369
Milk	8	4	Withheld
Eggs	4	Withheld	Withheld

4.3.2.2 WORKING ASSUMPTIONS

Again, as with the water supply sector, areas that receive low annual median rainfall are considered more vulnerable to drought than areas that receive higher rainfall. Using the same approach described in Section 4.3.1.2, terciles of high, medium, and low annual median rainfall were classified to locate areas that occur within the lower third of the median annual rainfall totals in each of the counties. Another assumption for this impact sector was that the non-irrigated lands are more vulnerable than irrigated lands, as non-irrigated lands receive moisture from precipitation and are therefore more susceptible to the effects of meteorological drought. Also assumed is that none of the extensive agriculture (livestock) lands are irrigated, as these lands are mostly grasslands and pasture.

Another assumption made for this analysis was to classify all crop production or cultivation as “intensive agriculture.” Livestock operations are classified as “extensive agriculture.” This distinction between “intensive” and “extensive” agriculture is important since crop production and livestock operations have different vulnerabilities to drought.

4.3.2.3 METHODOLOGY

Analysis of the Agriculture and Commerce Sector involved condensing all the different types of agricultural crop and livestock lands into just two types:

1) Intensive agriculture; and
2) Extensive agriculture.

Intensive agriculture is defined as a form of agriculture or cultivation that uses large amounts of labor and capital relative to the land area. Large amounts of labor and capital are necessary to the application of fertilizer, insecticides, fungicides, and herbicides to growing crops, and capital is particularly important to the acquisition and maintenance of high-efficiency machinery, and often some form of irrigation.

Extensive agriculture is defined as farming that is often practiced on larger farms, characterized by low levels of inputs per unit area of land. In such situations the stocking rate, the number of livestock units per area, is low. The crop yield in extensive agriculture depends primarily on the natural fertility of the soil, terrain, climate, and the availability of water. Land use layers acquired for each county were further refined to combine relevant agriculture categories into the respective use of intensive or extensive agriculture.

By using GIS interpolation routines, the total median annual rainfall isohyet data was converted into a continuous raster grid surface. This process provides interpolated data values between isohyets that would be necessary in the “Arithmetic Overlay” analysis. After the grid conversion was completed, terciles of high, medium, and low rainfall were created by splitting the rainfall data into equal thirds. The next step required converting the intensive agriculture and extensive agriculture layer into raster grid layers, so that they were compatible with the rain tercile grid data and so that the “Arithmetic Overlay” calculation process could be utilized to develop new layers. The "Arithmetic Overlay" allows the modeler to combine several input grid themes by assigning an operator and multiplier to each scheme. The main advantage is that it utilizes Boolean manipulation to scale and calculate intersections and overlapping areas. An additive arithmetic overlay process was conducted separately for intensive agriculture and extensive agriculture to produce the following layers:

1) Intensive agriculture and high rainfall;
2) Intensive agriculture and medium rainfall;
3) Intensive agriculture and low rainfall;
4) Extensive agriculture and high rainfall;
5) Extensive agriculture and medium rainfall; and
6) Extensive agriculture and low rainfall.

Table 4.4 to 4.7 illustrate the “Arithmetic Overlay” process.

Table 4.4 Arithmetic Overlay - Input Process, Intensive Agriculture

For Intensive Agriculture	For Rainfall Terciles
Intensive = 1	High = 3
	Medium = 2
	Low = 1

If we add the values of each grid cell, the result consist of 2s, 3s, or 4s which mean:

Table 4.5 Arithmetic Overlay - Output, Intensive Agriculture

2 = Intensive Agriculture and Low Rainfall
3 = Intensive Agriculture and Medium Rainfall
4 = Intensive Agriculture and High Rainfall

Table 4.6 Arithmetic Overlay - Input Process, Extensive Agriculture

For Extensive Agriculture	For Rainfall Terciles
Extensive = 1	High = 3
	Medium = 2
	Low = 1

Table 4.7 Arithmetic Overlay - Output, Extensive Agriculture

2 = Intensive Agriculture and Low Rainfall
3 = Intensive Agriculture and Medium Rainfall
4 = Intensive Agriculture and High Rainfall

Once this process was complete, because the output grid layers are continuous, a reclassification step was required to convert the grid layers to discrete layers. The final map layers produced allowed for the classification and determination of the most vulnerable locations statewide that met the criteria of involving a land use activity of either intensive or extensive agriculture that is located in a low rainfall zone.

4.3.2.4 DATA SOURCES

The data utilized for this analysis of the agriculture and commerce impact sector was again separated into two types of data layers:
1) Critical layers; and
2) Reference layers.

Again for illustrative purposes, the critical layers refer to GIS layers that are critical in the overall analysis of determining vulnerability, and the reference layers refer to layers used specifically to provide reference information to improve the ability to understand the situation that is occurring or where it is occurring.

The critical layers used in this analysis included each county's land use/zoning layer and the median annual rainfall layer. The zoning/land use maps were obtained from each of the county planning departments, and provide the most up-to-date information on land use to identify and distinguish lands that were of either intensive or extensive agriculture. The rainfall data was obtained from the DBEDT, Office of State Planning's GIS Program. Again, the rainfall data was originally in the form of isohyets and required conversion into a continuous grid surface to be used in this analysis.

Reference layers used to provide locational and informational content include a perennial stream layer, major road layer, and a ditches and reservoir layer. All these layers were obtained from the DBEDT, Office of State Planning's GIS Program. The layers were originally from the U.S. Geological Survey's Digital Line Graph (DLG) map series.

4.3.2.5 VULNERABILITY MAPS AND DISCUSSION OF RESULTS

The final maps and findings for the vulnerability analysis of the agriculture and commerce sector can be seen on Figure 4.5 to Figure 4.8. Figure 4.5, shows that a greater proportion of intensive and extensive agriculture activities in Hawaii County are within the low rainfall tercile along the Kona Coast, Lower and Upper Kohala region, and South Point, Kau District. A greater proportion of these vulnerable lands are extensive agriculture (livestock grazing lands) that are particularly dependent on rainfall rather than irrigation.

Maui County's agriculture sector (Figure 4.6) is highly vulnerable, with over 75 percent of its extensive and intensive agriculture lands falling within low rainfall areas. Vulnerable areas on the island of Maui are on the western end of the island, and include areas like Makawao, Kula, Lahaina, Ulupalakua, and Kapalua.

The islands of Molokai and Lanai are just as vulnerable within the agriculture and commerce sector. Other than areas along the eastern and south eastern slopes of the Molokai Forest Reserve, all of the lands in intensive and extensive agriculture are very vulnerable to drought due to a lack of rainfall. Like Molokai, Lanai's agriculture sector is very vulnerable to the effects of a meteorological drought. Based on the analysis results depicted in Figure 4.6, the areas in the central parts of the island are less prone to the effects, but a greater proportion of the extensive agriculture lands are very vulnerable.

The City and County of Honolulu has the fewest acres of land still dedicated to the agricultural industry, in terms of both intensive and extensive agriculture. This does not mean that the county is not vulnerable to the effects of meteorological drought. In fact, the low tercile rainfall areas coincide with a majority of the agricultural activities still existing on Oahu. Areas in the upper Ewa Plains of Kunia and the areas from Helemano to Haleiwa are highly vulnerable (Figure 4.7).

Kauai County (Figure 4.8) is mostly affected by meteorological drought in the agriculture lands along the southern and north western parts of the island. Majority of the agriculture services are in the intensive category located along the coastal areas in the south from Lawai to Mana. All of these lands are in the low end tercile for median annual rainfall.

4.3.2.6 CAVEATS AND DATA LIMITATIONS

Again, the data limitations are more specifically associated with the fact that the determination of agricultural lands was based on land use/zoning layers created by separate sources. Therefore, there is no common standard across counties, and there are noticeable differences in layers between counties. Also, because each county tends to categorize land use/zoning slightly differently, decisions had to be made on what categorizations would be summarized to fit the new categories of intensive and extensive agriculture. Intensive agriculture lands were determined more easily than extensive agriculture because most counties had some form of designation for agriculture, but extensive agriculture could have many interpretations, i.e., livestock, ranchland, grassland, etc.

Another limitation is that this aggregation of intensive agriculture does not take into account the fact that different crops require different amounts of water; hence the results may be somewhat misleading. Additional data layers and information on soil moisture, soil water retention, crop evapotranspiration, crop water requirements, along with updated layers on different crop lands would be more valuable to identify potential water deficits to intensive agriculture. Also useful would be information regarding irrigation practices as applied to the crop locations. This would provide an idea as to how much water is currently being supplied to the crops through irrigation.

As has been referred to earlier, the tercile division of rainfall may be too coarse for our analysis. Future refinement of the analysis involving additional division of the rainfall layer will have to be weighed against the visual clarity of the map products.

4.3.3 ENVIRONMENT, PUBLIC HEALTH AND SAFETY SECTOR

4.3.3.1 DESCRIPTION OF SECTOR

The environment, public health and safety sector is an examination of the vulnerability of human settlements to wildland fire. This sector is linked directly to the issues surrounding wildland-urban interface. The wildland-urban interface is an area where human settlements such as homes, ranches, and farms abut with areas considered wildlands. Urban expansion has driven both the increases in incidence and extent of the wildland-urban interface areas. Many individuals may desire to have a few acres of land and the seclusion of being on the outskirts of town, but what they may fail to realize is the increased danger from wildfire in these areas.

Drought is one of many factors contributing to the complexity of forest ecosystems adapted to frequent fires. Although drought increases the potential for catastrophic wildfire, drought cannot be singled out as the sole cause or key factor in wildfires. Other factors include wildland fuels accumulated during many decades of unwise fire suppression, overcrowded tree stands, and the overgrowth of brushes and grasses mixing with urban fuels at the wildland-urban interface. A more appropriate way of characterizing the relationship is that wildland fires tend to be induced by drought, and not caused by them.

Wildland fire is a growing and serious problem all over the United States, posing a threat to life and property, particularly when it moves from forest or rangeland into developed areas. Wildland fires leave behind them numerous secondary impacts. When wildland fires scorch and burn acres of forest land, steep slope areas become potential hazard areas for debris, mud, and rock flows during periods of torrential rains. During an intense wildland fire, all vegetation may be destroyed; also the organic material in the soil may be burned away or may decompose into water-repellent substances that prevent water from percolating into the soil. As a result, even normal rainfall may result in unusual erosion or flooding from a burned area and heavy rain can produce destructive debris flows. Water supplies are also affected by fire: the loss of ground-surface cover, such as needles and small branches, and the chemical transformation of burned soils hinder the watershed recharge rate, especially during heavy rainfall events.

Much of wildfire protection and prevention on state-owned lands within the State of Hawaii is managed by the Department of Land and Natural Resources, Division of Forestry and Wildlife (DOFAW), this authority falls under Hawaii Revised Statutes (HRS §185), under the Land Fire Protection Law. This law allows DOFAW to take measures for the prevention, control, and extinguishment of forest fires on state owned lands within forest reserves, public hunting areas, wildlife and plant sanctuaries and natural area reserves. It also stipulates that DOFAW shall cooperate with established fire control agencies of the counties and the federal government in developing plans and programs and mutual aid agreements to assist in the prevention, control, and extinguishment of forest, grass, brush, and watershed lands not within the department's fire protection responsibilities described above.[8]

According to DOFAW, from 1994 to 2002, there were a total of 1299 fires that burned 94,691.1 acres of wildland, although a greater proportion of the fires were of Class A and Class B, (Table 4.9) approximately 83 percent, the majority of the acreage scorched came from Class F and G fires (Table 4.9). Most of these fires were caused by arson and what DOFAW has categorized as miscellaneous, approximately 62 percent (Table 4.8).

Table 4. 8 Annual Wildfire Summary Report by Cause (1994 - 2002)

Year	Lightning		Campfire		Smoking		Debris burning		Arson	
	Number	Acres	Number	Acres	Number	Acres	Number	Acres	Number	Acres
1994	0.0	0.0	1.0	0.3	9.0	4.0	18.0	9.5	43.0	366.3
1995	0.0	0.0	7.0	3.9	29.0	440.8	14.0	2853.0	58.0	616.0
1996	2.0	2.2	12.0	6.1	14.0	18.3	18.0	37.4	21.0	106.1
1997	2.0	4.1	4.0	1.4	9.0	6.6	8.0	4.9	5.0	117.6
1998	0.0	0.0	9.0	0.9	16.0	2258.7	28.0	81.6	49.0	3291.5
1999	1.0	20.0	3.0	1.6	5.0	83.7	14.0	290.9	25.0	14173.9
2000	1.0	2.0	3.0	0.3	13.0	9.7	22.0	241.7	18.0	74.1
2001	0.0	0.0	8.0	6.3	13.0	16.3	7.0	17.7	13.0	117.6
2002	1.0	0.1	9.0	0.8	13.0	28.7	23.0	9.0	16.0	139.4
Total	7.0	28.4	56.0	21.6	121.0	2866.8	152.0	3545.7	248.0	19002.5

Year	Equipment		Railroads		Children		Miscellaneous	
	Number	Acres	Number	Acres	Number	Acres	Number	Acres
1994	3.0	14.1	0.0	0.0	2.0	0.4	48.0	19798.8
1995	14.0	1446.3	0.0	0.0	13.0	1213.5	82.0	2994.8
1996	13.0	109.7	0.0	0.0	9.0	3.1	41.0	183.8
1997	13.0	30.7	0.0	0.0	7.0	3.6	19.0	208.2
1998	16.0	847.8	0.0	0.0	11.0	2473.7	76.0	28360.6
1999	8.0	572.3	0.0	0.0	4.0	7.4	72.0	5226.0
2000	11.0	2197.6	0.0	0.0	13.0	12.7	44.0	393.2
2001	5.0	61.5	0.0	0.0	3.0	11.6	59.0	849.3
2002	7.0	0.7	0.0	0.0	5.0	1.8	117.0	2202.9
Total	90.0	5280.7	0.0	0.0	67.0	3727.8	558.0	60217.6

Source: Division of Forestry and Wildlife (DOFAW), DLNR

[8] Department of Land and Natural Resources, Division of Forestry and Wildlife. http://www.hawaii.gov/dlnr/dofaw/fmp/

Table 4.9 Annual Wildfire Summary Report by Size Type (1994 - 2002)

	Class A		Class B		Class C		Class D	
Year	**Number**	**Acres**	**Number**	**Acres**	**Number**	**Acres**	**Number**	**Acres**
1994	31	4	74	150.3	13	394	2	100.1
1995	89	11.9	87	184.4	25	666	7	1115
1996	58	6.4	54	92.3	18	368	0	0
1997	23	4.7	34	81.4	8	190	2	101
1998	68	9.9	77	148.9	36	2255	9	1896
1999	50	9.7	61	223.1	16	408	1	235
2000	48	6.8	60	146.4	12	270	2	350.1
2001	40	11.1	44	133.2	23	545	0	0
2002	148	15.5	29	62.9	12	350	1	255
Total	555	80	520	1222.9	163	5446	24	4052.2

	Class E		Class F		Class G	
Year	**Number**	**Acres**	**Number**	**Acres**	**Number**	**Acres**
1994	3	1545	1	18000	0	0
1995	6	2367	2	2404	1	2820
1996	0	0	0	0	0	0
1997	0	0	0	0	0	0
1998	9	4895	5	15657	1	12453
1999	1	500	1	4000	2	15000
2000	2	1150	1	1008	0	0
2001	1	391	0	0	0	0
2002	0	0	1	1700	0	0
Total	22	10848	11	42769	4	30273

Class A - 0.25 acres or less
Class B - 0.26 to 9 acres
Class C - 10 to 99 acres
Class D - 100 to 299 acres
Class E - 300 to 999 acres
Class F - 1000 to 4999 acres
Class G - 5000 acres or more
Source: Division of Forestry and Wildlife (DOFAW), DLNR

4.3.3.2 WORKING ASSUMPTIONS

Rainfall is critical in contributing to surface water/moisture, groundwater, and overall vegetation health; hence it has been included as a component of each of the impact sector analyses. Again, low rainfall areas are assumed to be of higher vulnerability because the lack of moisture in vegetation increases the opportunity for fires to start and spread more readily. With this assumption in mind, classification of the median annual rainfall into terciles of high, medium and low rainfall is one of the easiest ways to illustrate where a lack of rain can contribute to increases in wildland fires. Although, high temperatures, low humidity, and low rainfall increase the likelihood of fire, wildfires can occur anywhere, hence the need to use other correlating factors to evaluate wildfire vulnerability.

Within the wildland-urban interface or even within the wildlands themselves, vegetation or land cover is assumed to be an indicator of vulnerability. Different fire fuels react and burn differently based on moisture content and relative greenness (alive or dead), but different land/vegetation cover tend to determine the type of fire that may occur, hence, increasing the vulnerability of those in the vicinity. According to the National Oceanic and Atmospheric Association's (NOAA) National Fire Danger Rating System[9] (NFDRS) there are four types of wildland fires, each with its own distinct burn pattern and controllability based on factors such as moisture, wind, slope, and topography, but also on the type of vegetation. Based on the NFDRS, there are ground fires, surface fires, crown fires, and spotting fires. Ground fires burn within the natural litter, roots, and high organic soils of the wildland areas, and once these fires start, they are difficult to detect and control. Often times these fires rekindle after being thought to be extinguished. Surface fires tend to burn in grasses and low shrubs, and tend to move very rapidly. Crown fires burn in the tops of trees, and once they are started, they are difficult to control. The wind plays an important factor in the severity of crown fires. Spotting fires can be produced by crown fires, wind factors, and topography, as embers are thrown ahead of the main fire. Depending on the vegetation, spotting fires can be particularly difficult to control.

Another assumption, specifically for this analysis, was that the U.S. Census Bureau's boundaries for the Census Designated Places (CDP) were used to delineate "Communities at Risk." "Communities at Risk" is a term that was developed by the National Fire Plan[10] to represent those communities that are at the wildland-urban interface and are at risk to wildland fires. Although the National Fire Plan does designate several of Hawaii's communities, the plan only selected communities that were in the vicinity of federally managed lands. Those communities listed in Table 4.10 are the selected "Communities at Risk" under the National Fire Plan. Another solution had to be developed to include a broader classification of what should be considered a "Community at Risk." The CDP was chosen because it was the best "federally" recognized population based statistical boundary that resembled settled, named communities containing a mixture of residential, commercial and retail areas. According to the U.S. Census Bureau, each CDP contains an identifiable core encompassing the area that is associated strongly with the CDP name and contains the majority of the CDP's population, housing, commercial structures, and economic activity.[11] A CDP must comprise a reasonably compact and continuous land area internally accessible to all points by road. Prior to the 2000 Census, a CDP required a population of 2500 people, but currently there are no minimum or maximum population thresholds for recognition as a CDP.

The main assumption used in this analysis is that since wildland fires tend to occur in the same places time and time again, past burn areas are highly vulnerable. This is primarily due to the fact that most wildland fires occur at this wildland-urban interface, many times along road corridors and near interface communities. Although wildland fires are natural occurring events that help maintain ecological balances within the wildland ecosystem, it is important to note that most fires are either caused by human negligence, arson, or accidents.

[9] http://www.seawfo.noaa.gov/fire/olm/nfdrs.htm
[10] http://www.fireplan.gov/communities_at_risk.cfm
[11] http://www.census.gov

Table 4.10 National Fire Plan's Communities at Risk

Communities at Risk	Information
Aiea, HI	In the vicinity of Federal lands other than those managed by the Departments of Agriculture and the Interior
Aliamanu-Salt Lake, HI	In the vicinity of Federal lands other than those managed by the Departments of Agriculture and the Interior
Ewa, HI	
Fern Acres, HI	
Fern Forest, HI	
Glenwood, HI	
Hawaii Kai, HI	In the vicinity of Federal lands other than those managed by the Departments of Agriculture and the Interior
Kailua-Kona, HI	
Kaneohe, HI	In the vicinity of Federal lands other than those managed by the Departments of Agriculture and the Interior
Kapoho, HI	In the vicinity of Federal lands other than those managed by the Departments of Agriculture and the Interior
Kaupo, HI	
Kawaihae, HI	
Kekaha, HI	In the vicinity of Federal lands other than those managed by the Departments of Agriculture and the Interior
Kilauea, HI	
Kipahulu, HI	
Kokee, HI	In the vicinity of Federal lands other than those managed by the Departments of Agriculture and the Interior
Koolauloa, HI	
Makakilo Mauka, HI	In the vicinity of Federal lands other than those managed by the Departments of Agriculture and the Interior
Makakilo/Kapolei, HI	In the vicinity of Federal lands other than those managed by the Departments of Agriculture and the Interior
Mililani Mauka, HI	
Mililani-Waipio, HI	In the vicinity of Federal lands other than those managed by the Departments of Agriculture and the Interior
Moanalua, HI	In the vicinity of Federal lands other than those managed by the Departments of Agriculture and the Interior
Mokapu, HI	In the vicinity of Federal lands other than those managed by the Departments of Agriculture and the Interior
North Shore, HI	In the vicinity of Federal lands other than those managed by the Departments of Agriculture and the Interior
Pearl City, HI	In the vicinity of Federal lands other than those managed by the Departments of Agriculture and the Interior
Volcano, HI	
Wahiawa, HI	In the vicinity of Federal lands other than those managed by the Departments of Agriculture and the Interior
Waianae Coast, HI	In the vicinity of Federal lands other than those managed by the Departments of Agriculture and the Interior
Waimanalo, HI	In the vicinity of Federal lands other than those managed by the Departments of Agriculture and the Interior
Waipahu, HI	In the vicinity of Federal lands other than those managed by the Departments of Agriculture and the Interior

4.3.3.3 METHODOLOGY

This sector analysis is based on the idea that proximity of past wildland fires to the Census Designated Places (CDP) or "Communities at Risk" will provide some indication as to how vulnerable a community may be, based on the assumption that wildfires tend to reoccur in the same areas. To tackle this problem, paper maps of wildfires from the past 20 years were gathered and converted to a GIS format so that they could be overlaid on to the "Communities at Risk" layers. In addition, a major roadways layer was also included given that roads have multiple functions in relation to wildfire; access by firefighting crews, man–made fire breaks, and in some cases wildfire expansion corridors. Overlaying median annual rainfall terciles of High, Medium, and Low, provided further clarification of vulnerability. Communities that are both low rainfall and in close proximity to past wildland fires would be considered most vulnerable to future wildland fires. Other reference layer information served to flesh out vulnerability and potential burn patterns. For example, wildfires that span multiple land uses, which can be inferred as having different ground cover, tend to be associated with different burn patterns or burn characteristics.

4.3.3.4 DATA SOURCES

As with the analyses of the other impact sectors, the analysis on the Environment, Public Health and Safety sector included two types of data layers: Critical layers, and Reference layers. The critical data layers used in this analysis included:

1) Past statewide wildland fire burn areas;
2) Median annual rainfall classified into terciles of High, Medium, and Low rainfall zones; and
3) Census designated places (CDP) that designate "Communities at Risk".

The past wildland fire burns areas were compiled by the State Department of Land and Natural Resources (DLNR), Division of Forestry and Wildlife (DOFAW). The paper maps consisted of fires statewide over the past 20 years. Other wildland fire GIS data was obtained from U.S. Department of Interior's Fish and Wildlife Service (USFWS). Table 4.11, shows the dates and approximate acreage burned for each of the wildfire maps provided by DOFAW and USFWS. Hawaii County had 48 map-recorded wildland fires from 1953 to 2001, with a total of 90,159.19 acres burned. Maui County had 42 map-recorded wildland fires from 1980 to 2002, burning a total of 30,016.48 acres. The City and County of Honolulu had 9 map-recorded wildland fires from 1998 to 2002, burning a total of 3903.027 acres. Kauai County has had fewest number of wildland fires over the map recorded times, both in number and acreage. For a period from 1998 to 2000, Kauai County had 5 wildland fires, which burned a total of 29.49 acres.

The median annual rainfall data was obtained from the DBEDT Office of State Planning GIS Program. The original data was in the form of isohyets, and were converted through GIS interpolation algorithms to a raster grid dataset, which was then classified into terciles of High, Medium, and Low rainfall vector polygon zones.

The Census Designated Places on which "Communities at Risk" was based, was obtained from the U.S. Census Bureau for the Census 2000. As mentioned previously, this dataset is statistical based population boundary file that includes residential, commercial, and retail units within a named community.

The reference layers used in this analysis included:

1) Reservoirs;
2) Major roads; and

3) The State of Hawaii land use districts.

The reservoir layer was obtained from the DBEDT Office of State Planning GIS Program, but was originally from the U.S. Geological Survey's Digital Line Graph (DLG) dataset. The reservoir data layer provides reference as to where potential fire suppression surface water sources may exist.

The major roads data layer was also obtained from the State of Hawaii's Department of Business, Economic Development and Tourism's Office of State Planning GIS Program, but was originally a part of the U.S. Geological Survey's Digital Line Graph (DLG) dataset. The major roads were selected to provide a frame of reference as too where corridors may exist between "Communities at Risk" and wildland zones (Wildland-Urban Interface). Although other road layers exist, most of which include all types of roads, the major roads layer was chosen because of its simplicity, yet its ability to provide the necessary information.

The State of Hawaii land use districts were also obtained from the DBEDT Office of State Planning GIS Program. As previously mentioned in Section 4.3.1.4, the state land uses are classified based on a land use boundary code (ludcode) of either:

1) A – Agricultural Land Use District;
2) C – Conservation Land Use District;
3) R – Rural Land Use District; or
4) U - Urban Land Use District.

This layer provides background information that when used in combination with the CDP layer, allows the map interpreter to determine if the "Community at Risk" is more of a farming community, rural, or urban. Keep in mind that these designations are very general, and should only provide a broad view of the overall land uses.

4.3.3.5 VULNERABILITY MAPS AND DISCUSSION OF RESULTS

The results of this analysis can be examined in Figures 4.9 to 4.12. Hawaii County (Figure 4.9) has had the most wildland fires; approximately 48 fires, burning a total of 90,159.19 acres (Table 4.11). Twenty-nine out of the 48 total fires were on the western end of the island in the proximity of the Waikoloa Village "Community at Risk". These Waikoloa Village fires burned a total of 78,752.88 acres and ranged from actually occurring within the community to as far as 11.67 miles from the community. According to the U.S. Census Bureau's figures, the Waikoloa Village CDP has a population of 4,806 people. Although other "Communities at Risk" have greater populations, vulnerability in this analysis is primarily a function of proximity. Therefore, Waikoloa's vulnerability is considered greater than that of other "Communities at Risk." When combining the past burn areas layer and the rainfall tercile layer, it is apparent that "low rainfall" zones increase the odds of wildfire occurrences. A total of 40 of the 48 fires in Hawaii County from 1953 to 2001 occurred in "low rainfall" zones. Also, due to the infrequency of lightning strike-induced fires (Table 4.8), and since most of the wildfires occurred in either agriculture or conservation land use zones, it may be assumed that a greater proportion of these fires were started by human negligence or arson rather than by natural means.

Over a period from 1980 to 2002, Maui County had a total of 42 fires, burning over 30,000 acres of land (Table 4.11). Over this period, the Kauanakakai "Community at Risk" on the island of Molokai had 15 wildland fires, 5 in 1998 alone, consuming a total of 13,618.52 acres of land. On the island of Maui, the Waikapu "Community at Risk" had 11 wildland fires from 1980 to 2002, with 6 in 1991 alone. These fires consumed a total of 8,483.85 acres. A greater proportion of these wildland fires occurred in precipitation zones that have been designated as “low rainfall,” hence further strengthening the association or correlation of wildfire and low rainfall (Figure 4.10). Examination of the analysis results show that within Maui County, not only are the fires located in “low rainfall” zones, but the greater proportion of the wildland fires are occurring within proximity of populated areas and not in remote locations (Figure 4.10). Again, the interpretation is that a greater proportion of these fires were started by human negligence or arson, rather than by natural means.

The City and County of Honolulu, according to the map data, had 9 fires from 1998 to 2002, 5 of which were located in the Waipio “Community at Risk” (Table 4.11). Four of the fires occurred in 2002 alone and were located between communities, hence endangering more than one community. According to Figure 4.11, the City and County of Honolulu, has the largest number of “Communities at Risk,” primarily due to the fact that 72 percent of the population lives in the City and County of Honolulu, and there is a larger mix of urban/rural land to open land (approximately 35 percent, as compared to Maui County (5%), Kauai County (5%), and Hawaii County (2%) (Table 4.12)). This can be interpreted as a density factor or a built-up area to open land ratio which can be very dangerous during a wildland fire (Figure 4.11). Based on Figure 4.11, most of the wildland fires in the City and County of Honolulu have taken place on the central to western end of the island, either in “low rainfall” locations or between zones of low to medium rainfall within agriculture lands. Some areas, like the Waipio burn location mentioned previously, abut communities along major road corridors. Many times, wildland fires begin from acts such as flicking a lit cigarette out a car window or not extinguishing a campfire. The results of such human negligence and arson can be particularly pronounced during the typical wildland fire season of June to September, a period which can be prolonged by drought. According to the State of Hawaii, Department of Land and Natural Resources, Division of Forestry and Wildlife, Fire Management Program, 99.9 percent of the wildfires in Hawaii are human-caused.[12] This includes the wildland fires in the remote areas of the Leeward Coast of Oahu, i.e., Waianae Valley and Kaena Point. Some of the fires have also been known to be caused by military exercises occurring in the Makua Valley Military Training Grounds.

Kauai County has had the fewest incidences of wildfires despite drought conditions. Although Kauai, is known for its relatively wet weather, most “high rainfall” zones are situated high in the central mountains on conservation land (Figure 4.12). Much of the “medium rainfall” zones are likewise located in the central area of the island, in remote mountainous areas. As such, a greater portion of the island falls within the “low rainfall” category (Figure 4.12). The wildfires that have been mapped have actually occurred in conservation or agriculture land, with the distances to “community at risk” ranging from 1.3 miles away to 16.2 miles away (Table 4.11). Hence, from this analysis, wildland fires may not appear to be much of a problem on Kauai, but as stated previously, wildland fires can occur anywhere, even if the vulnerability appears to be low.

[12] Source: Email from Mr. Wayne F. Ching and Mr. Patrick G. Costales, State of Hawaii, Department of Land and Natural Resources, Division of Forestry and Wildlife, Fire Management Program. November 10, 2003.

Table 4.11 Wildland Fires in the State of Hawaii

County	Year	No.	Total Acreage	Closest CDP	Distance	CDP Pop (Yr 2000)
Hawaii	1953	1	3,681.34	Waimea	10.4 Miles	7,208
	1969	1	2,616.55	Waikoloa Village	3.02 Miles	4,806
	1972	1	8.966	Waimea	5.76 Miles	7,208
	1973	8	7,223.44	Waikoloa Village	4.46 Miles	4,806
	1975	2	342.209	Waimea	11.19 Miles	7,208
	1976	2	5.047	Honalo	12.82 Miles	1,987
	1977	2	1,065.11	Waimea	11.05 Miles	7,208
	1978	1	35.42	Waikoloa Village	11.67 Miles	4,806
	1983	1	5.82	Waikoloa Village	5.10 Miles	4,806
	1985	1	24,270.08	Waikoloa Village	3.28 Miles	4,806
	1987	3	11,701.20	Waikoloa Village	0 Miles	4,806
	1988	1	575.452	Kalaoa	6.15 Miles	6,794
	1989	1	3,318.15	Puako	2.14 Miles	429
	1991	2	215.831	Kalaoa	6.28 Miles	6,794
	1993	4	1,451.91	Waikoloa Village	6.14 Miles	4,806
	1994	2	714.632	Honalo	12.42 Miles	1,987
	1995	3	1,408.47	Kailua	2.88 Miles	9,870
	1996	1	72.988	Waikoloa Village	6.23 Miles	4,806
	1998	5	12,666.38	Waikoloa Village	0.84 Miles	4,806
	1999	4	18,709.09	Waikoloa Village	0.38 Miles	4,806
	2001	2	71.106	Kailua	14.22 Miles	9,870
Maui	1980	4	4,829.06	Kualapuu	0 Miles	1,936
	1984	5	2,003.21	Kihei	0.85 Miles	16,749
	1985	1	0.269	Wailea-Makena	4.11 Miles	5,761
	1987	4	970.061	Kaunakakai	2.33 Miles	2,726
	1988	2	83.581	Waikapu	0.48 Miles	1,115
	1989	2	31.264	Waikapu	0.39 Miles	1,115
	1990	4	207.659	Lanai City	1.34 Miles	3,164
	1991	6	8,320.79	Waikapu	2.55 Miles	1,115
	1992	3	315.761	Kaunakakai	1.45 Miles	2,726
	1993	3	217.51	Kaunakakai	2.00 Miles	2,726
	1995	1	48.217	Waikapu	1.87 Miles	1,115
	1998	5	12,145.19	Kaunakakai	0 Miles	2,726
	2001	1	547.524	Lahaina	2.27 Miles	9,118
	2002	1	296.384	Lahaina	3.45 Miles	9,118
Kauai	1998	1	1.328	Waimea	5.00 Miles	1,787
	1999	2	16.167	Waimea	6.85 Miles	1,787
	2000	2	12.001	Hanalei	10.44 Miles	478
Honolulu	1998	4	864.808	Mokuleia	1.08 Miles	1,839
	2000	1	272.969	Waipio	0 Miles	11,672
	2002	4	2,765.25	Pearl City, Waipio	0 Miles	30,976/11,672

Note: The Closest CDP does not reflect each individual fire, but the entire year's fires as a whole.

Table 4.12 Ratio of Developed Land Use to Open Land, Acreage Division

County	Total Acreage	Urban	Conservation	Agriculture	Rural	Ratio
Hawaii	2573400	53115	1304818	1214732	735	2%
Maui	465800	21409	194836	245777	3778	
Lanai	90500	3257	38197	46639	2407	
Molokai	165800	2539	49768	111627	1866	
Maui Total	722100	27205	282801	404043	8051	5%
Oahu	386188	99686	156618	129884	0	35%
Kauai	353900	14550	198769	139328	1253	5%
Total	4757688	221761	2225807	2292030	18090	

Source: State of Hawaii, Department of Business, Economic Development and Tourism, 2003 Hawaii State Databook

4.3.3.6 CAVEATS AND DATA LIMITATIONS

It should be noted that there are some limitations associated with the data used for this particular analysis. Although several of the wildfire locations were provided with acreage amounts, the digital map area does not necessarily reflect this exact acreage due to the fact that the paper maps from which the digital GIS data were created were not produced exactly to land survey accuracy standards. The paper maps were probably used as a means of record keeping for fire locations, rather than for purposes of spatial analysis. For this reason, distances to "communities at risk" should be considered approximations.

It should be noted that, having consulted with the State of Hawaii's Department of Land and Natural Resources' Division of Forestry and Wildlife, an informed decision was made on the direction of this analysis. It was determined that an analysis involving detailed information on vegetation cover, moisture (greenness), slope, topography, and wind direction and acceleration would shift the focus of this report to fire behavior, rather than vulnerability. The current analysis places greater emphasis on proximity and, as such, wildfire behavior could be an important area for further research. In addition, as mentioned previously, although low rainfall, low humidity levels, and high temperatures may increase the likelihood of fires, and although it appears that there is a strong likelihood of fires occurring in same locations as past fires based on the mapped data, fires can occur anywhere.

As has been referred to earlier, the tercile division of rainfall may be too coarse for our analysis. Future refinement of the analysis involving additional division of the rainfall layer will have to be weighed against the visual clarity of the map products.

Figure 4.1. Drought Vulnerability
Water Supply Sector, County of Hawaii

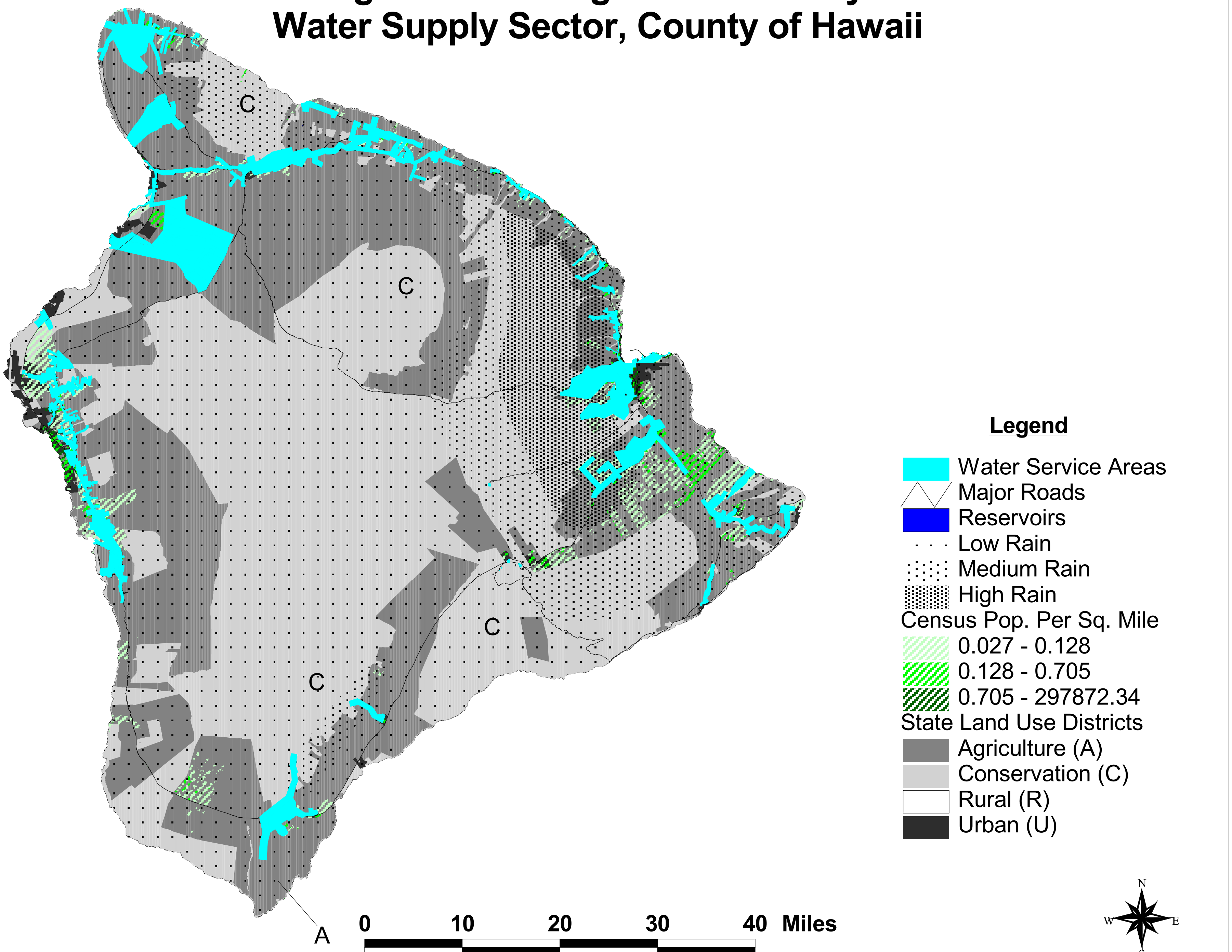


Figure 4.2 Drought Vulnerability
Water Supply Sector, County of Maui

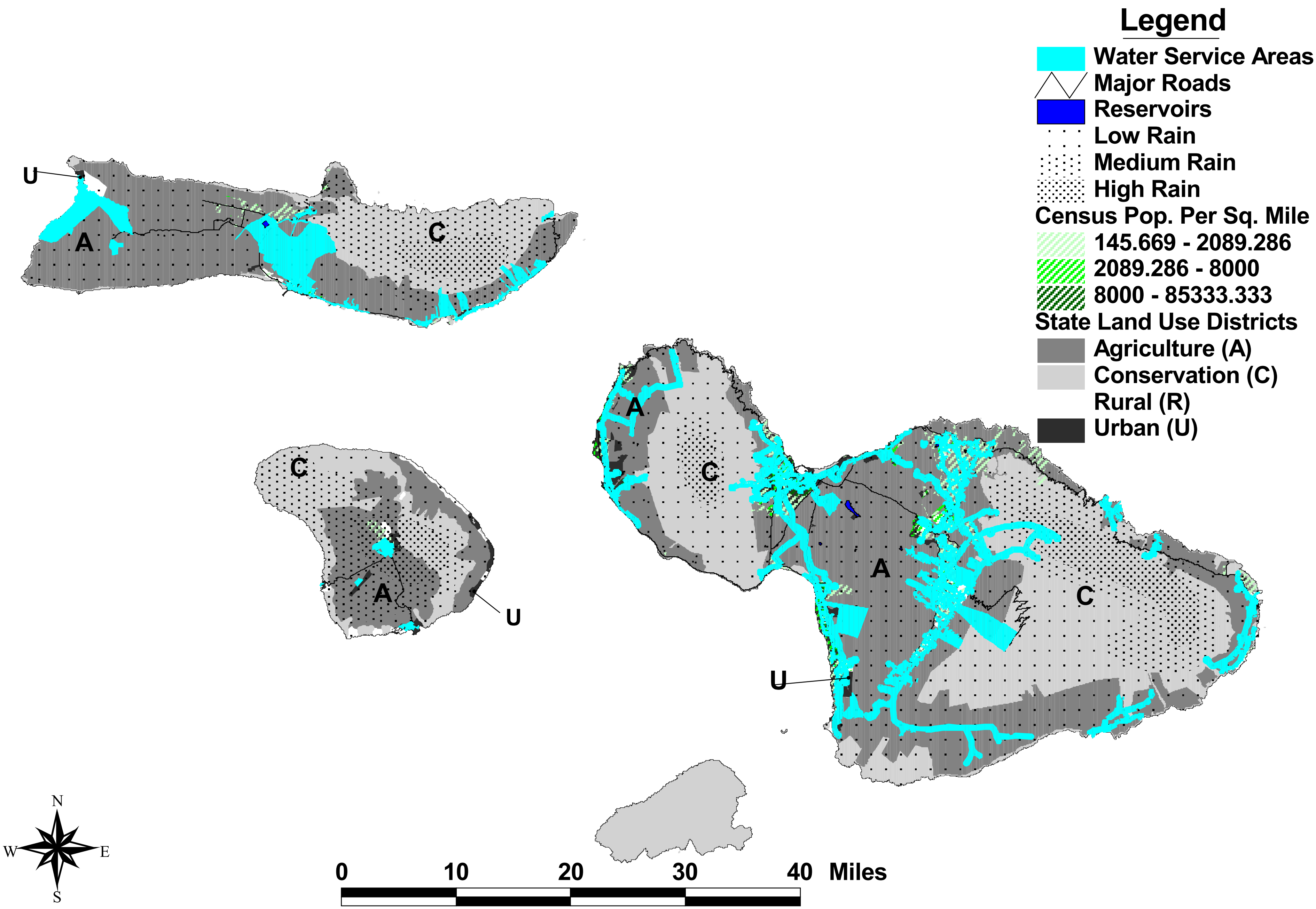


Figure 4.3. Drought Vulnerability
Water Supply Sector, City and County of Honolulu

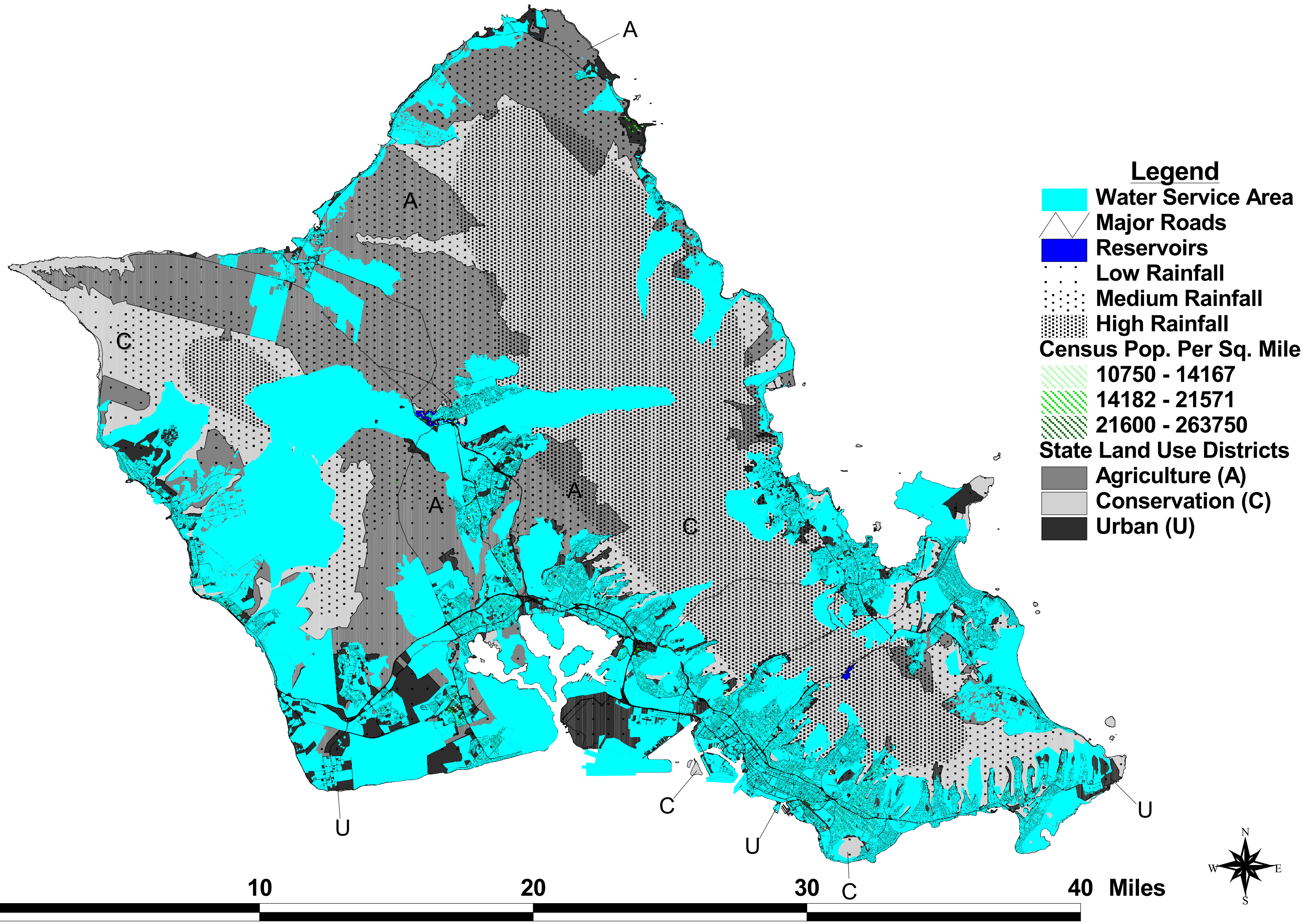


Figure 4.4 Drought Vulnerability Water Supply Sector, County of Kauai

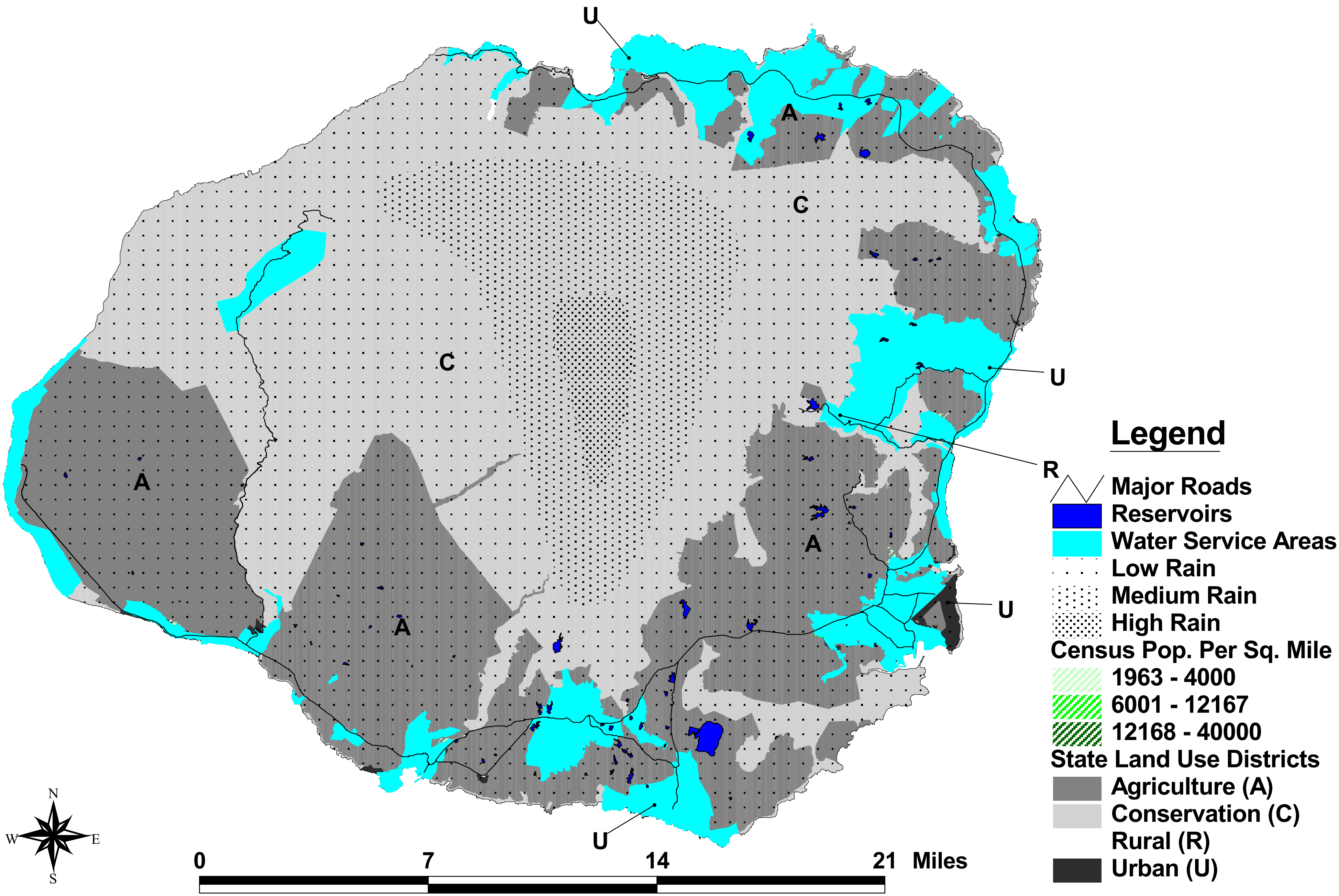


Figure 4.5. Drought Vulnerability
Agriculture Sector, County of Hawaii

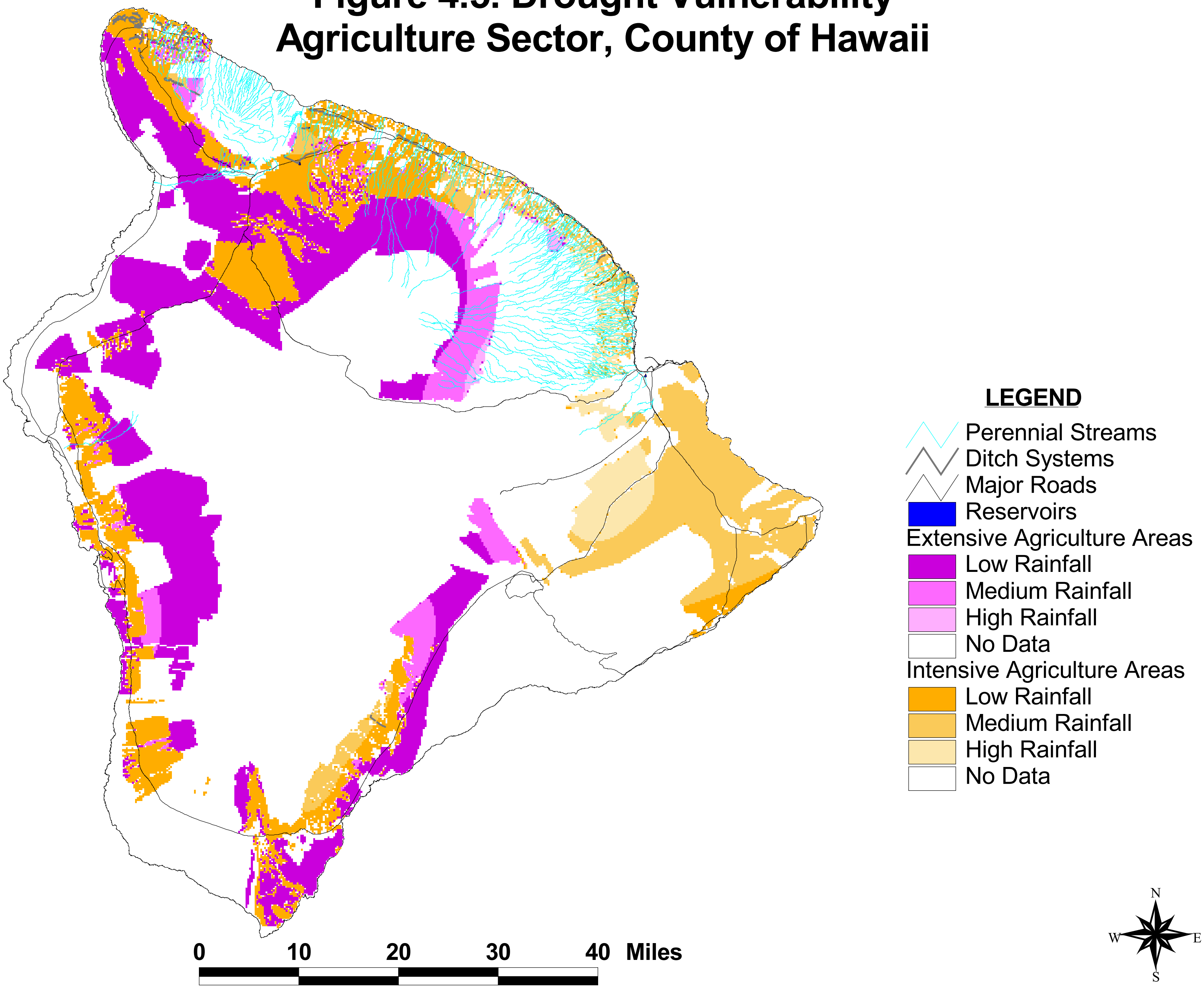


Figure 4.6. Drought Vulnerability Agriculture Sector, County of Maui

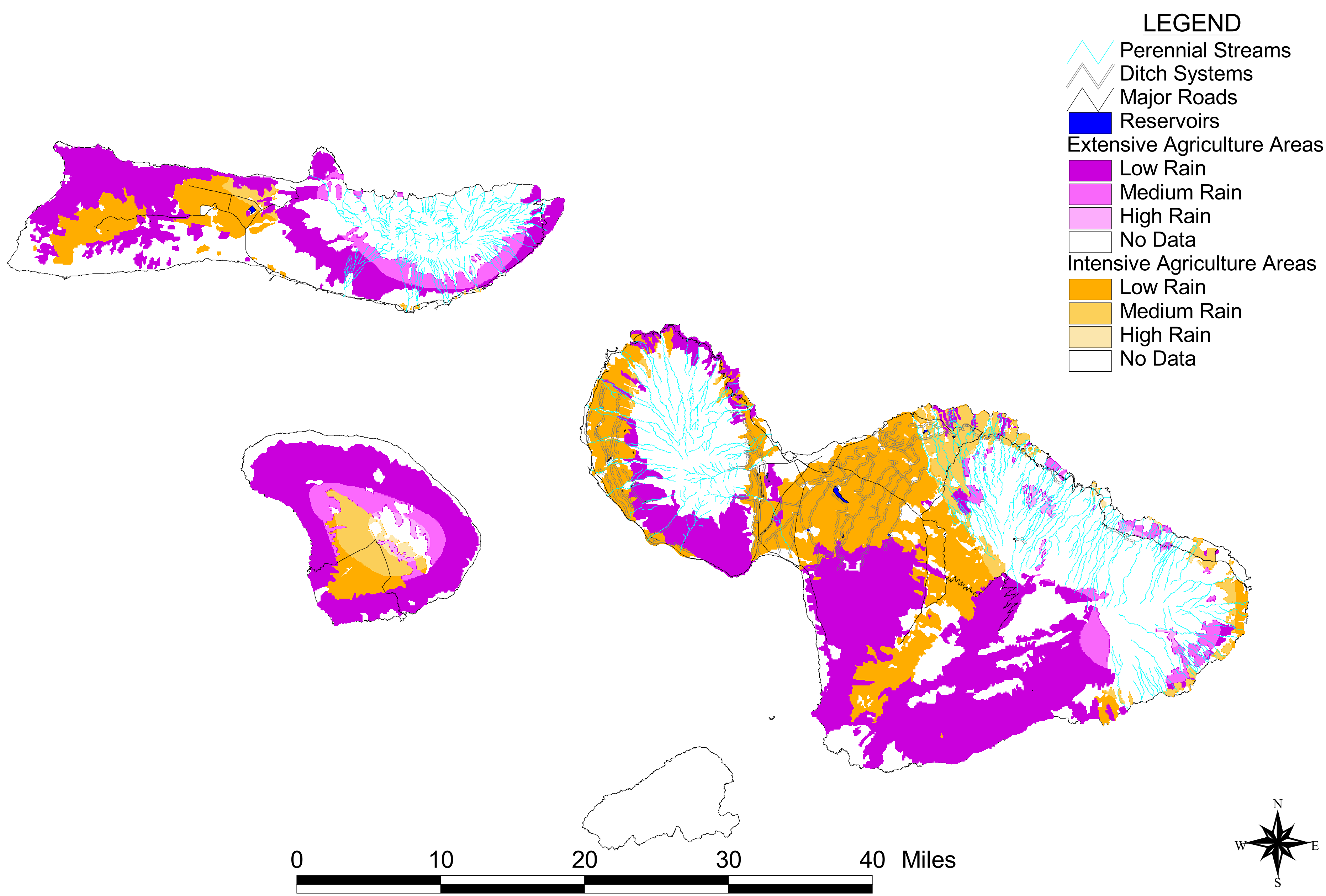


Figure 4.7 Drought Vulnerability
Agriculture Sector, City and County of Honolulu

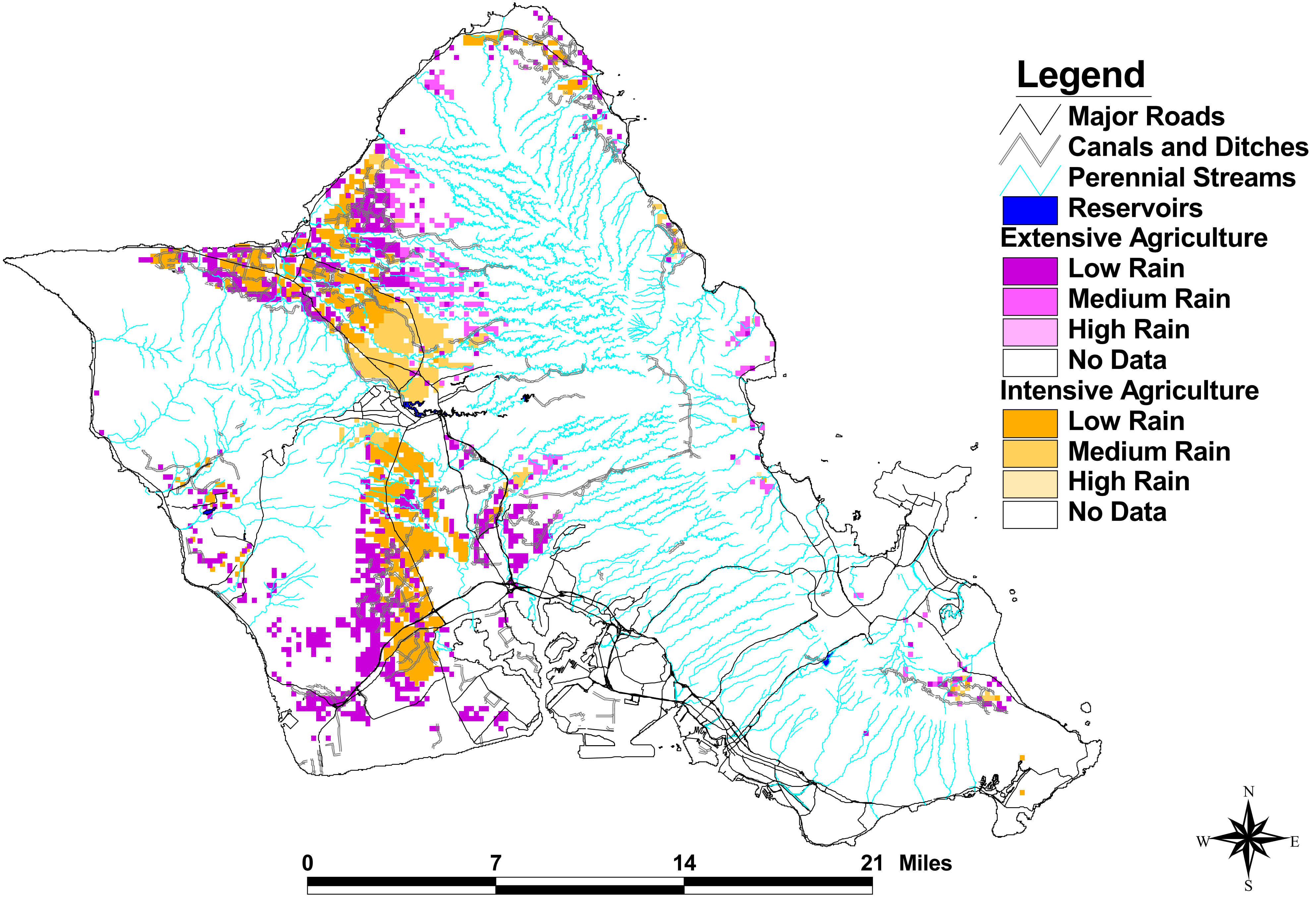


Figure 4.8 Drought Vulnerability
Agriculture Sector, County of Kauai

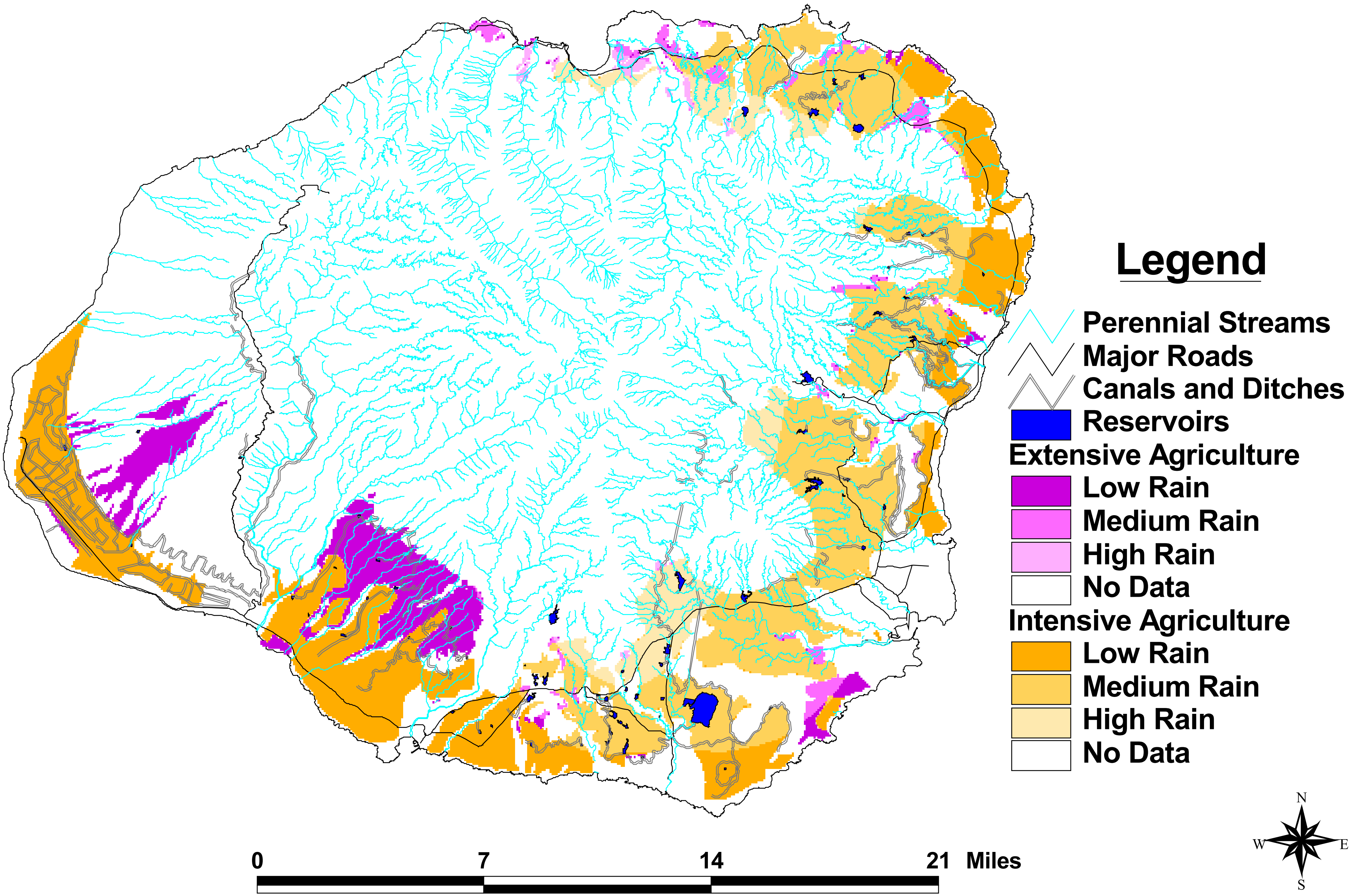


Figure 4.9. Drought Vulnerability
Environment, Public Health, and Safety Sector, County of Hawaii

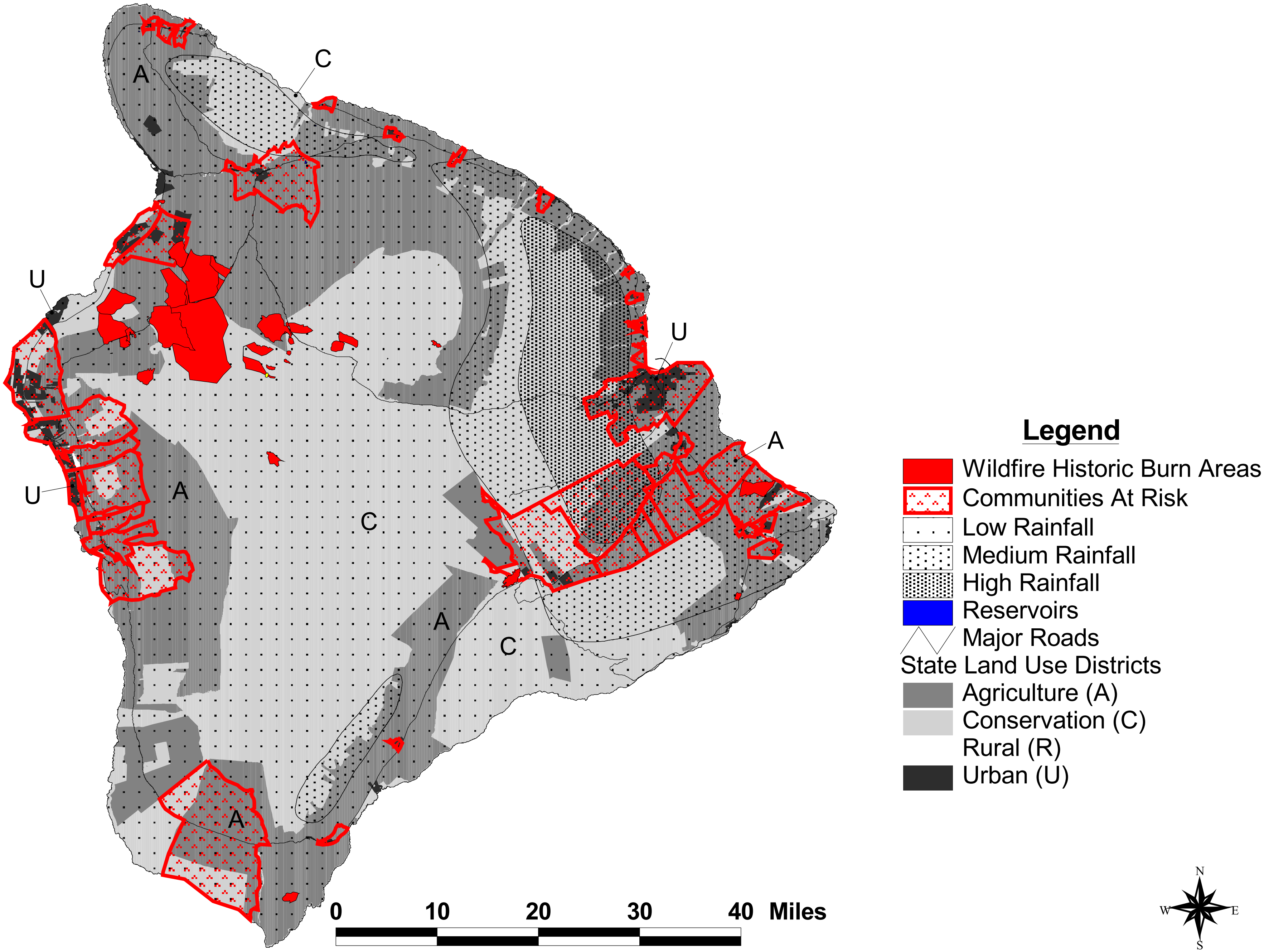


Figure 4.10. Drought Vulnerability
Environment, Public Health, and Safety Sector, County of Maui

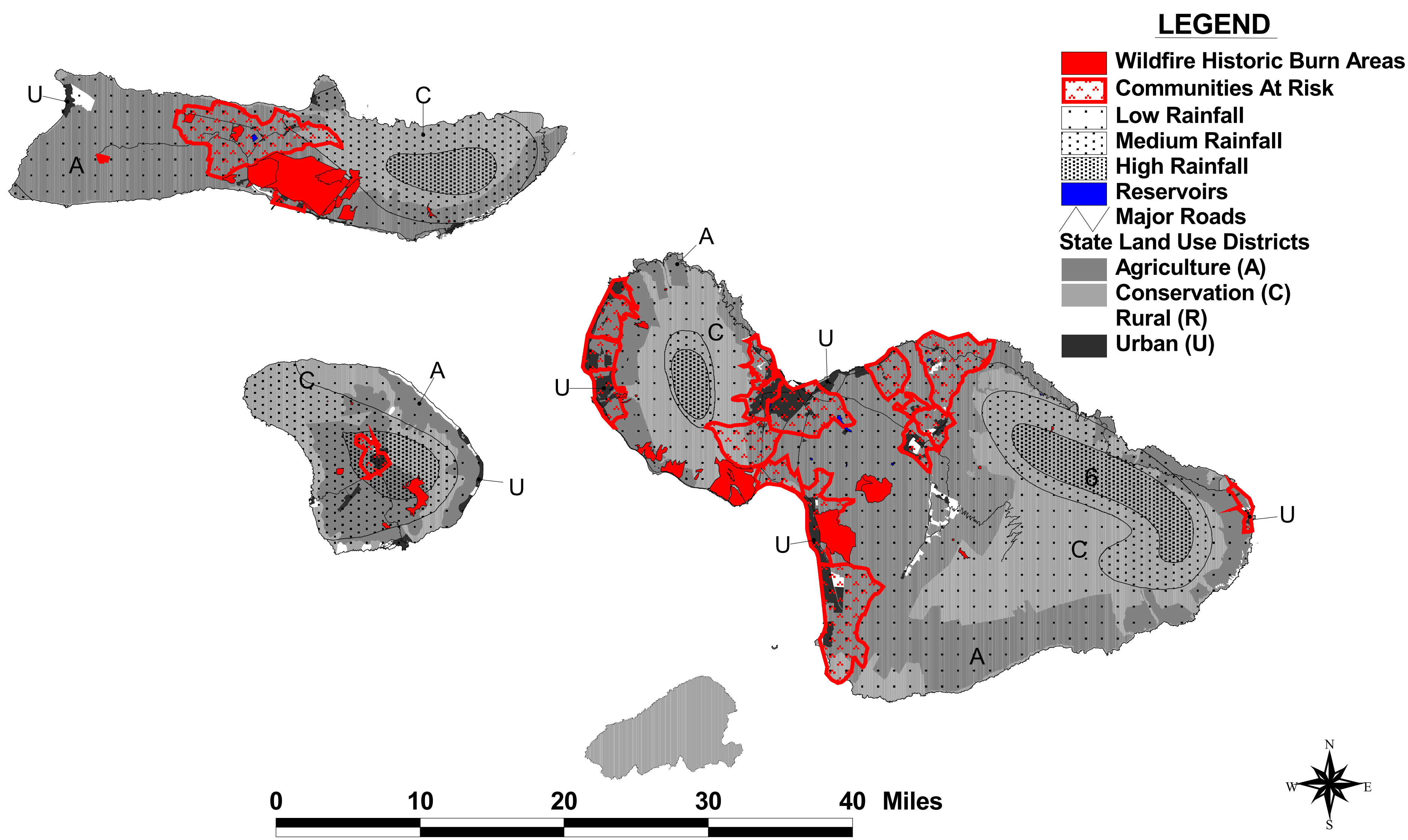


Figure 4.11. Drought Vulnerability
Environment, Public Health, and Safety Sector, City and County of Honolulu

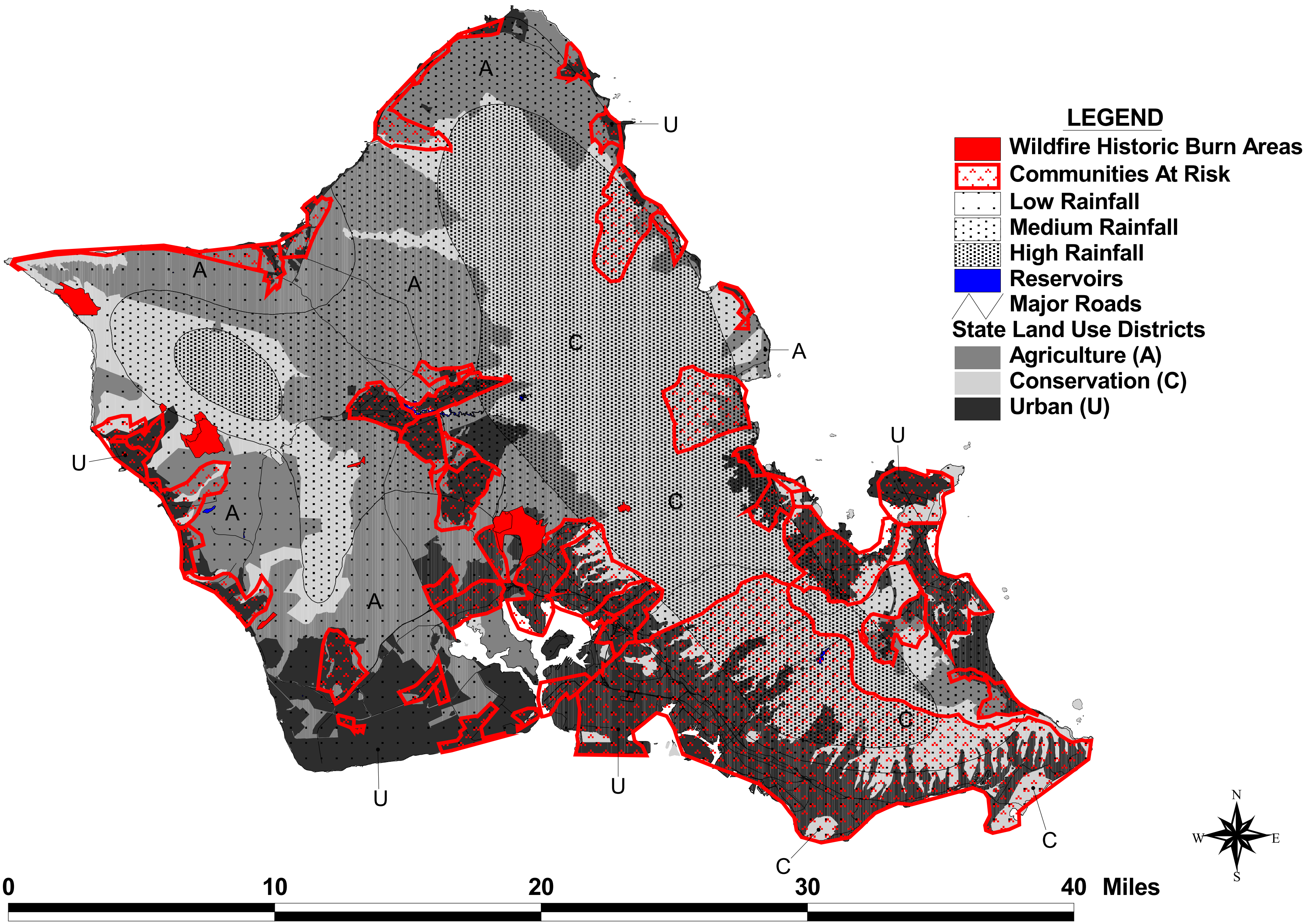
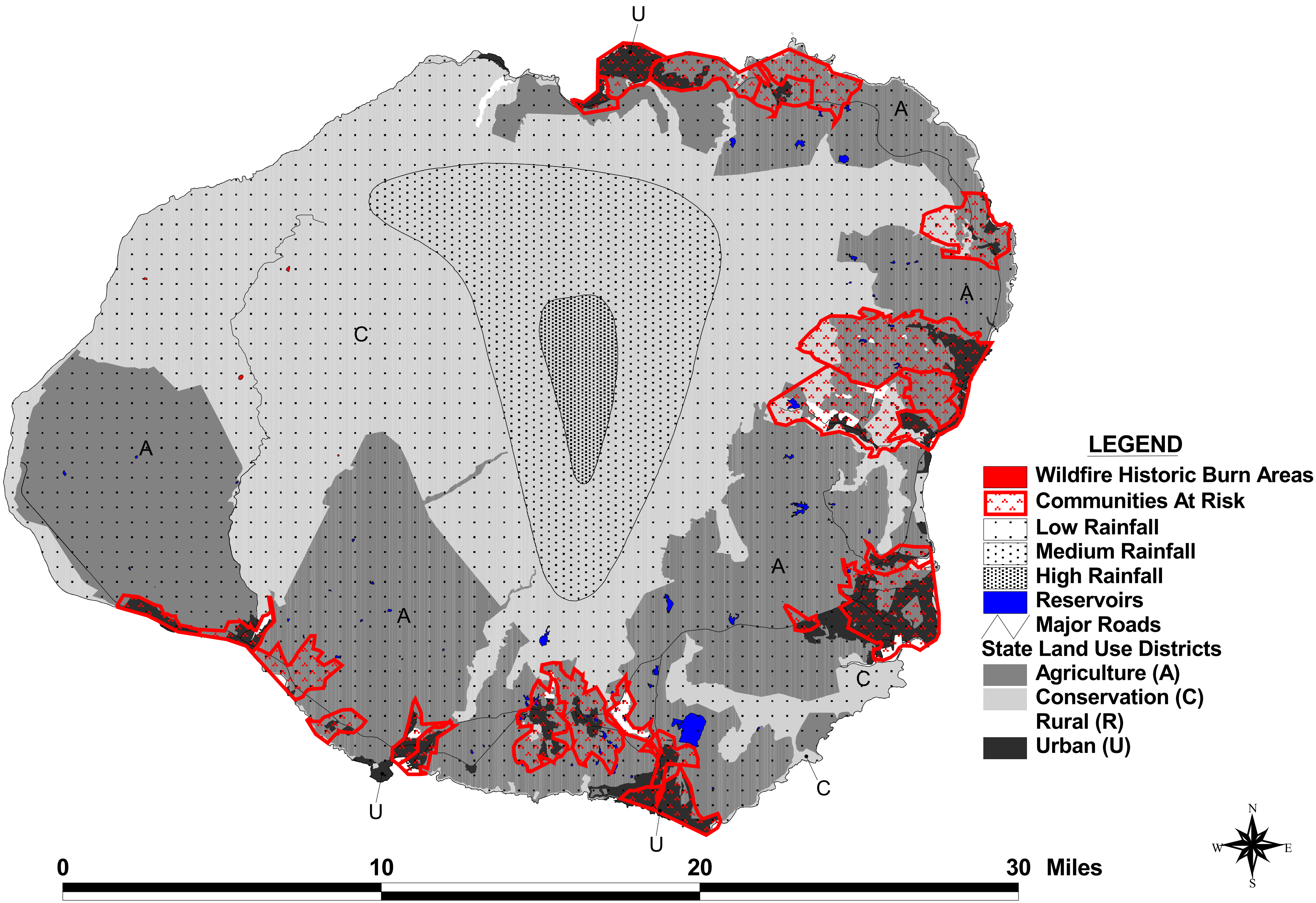


Figure 4.12. Drought Vulnerability Environment, Public Health, and Safety Sector, County of Kauai



5. STATEWIDE DROUGHT RISK AND VULNERABILITY ASSESSMENT

5.1 PURPOSE AND METHODOLOGY

The purpose of this component of the study is to integrate the Drought Frequency Analysis as discussed in Section 3 and the Drought Vulnerability Analysis as discussed in Section 4 to produce a tool to evaluate the risk of drought for each of the four counties. Keep in mind that, for the purposes of this report, drought risk is a combination of drought frequency and vulnerability. This risk may then be interpreted as the possibility of a drought impact occurrence. The impact could take a number of forms but this study focuses on evaluating the risk and vulnerability to three sectors: Public Water Supply Sector, Agriculture and Commerce Sector, and the Environment, Public Health and Safety Sector.

The approach taken for this risk assessment relies on the document entitled "How to Reduce Drought Risk" by the Western Drought Coordination Council. In this Statewide Drought Risk and Vulnerability Assessment, the concept of drought is expressed as a function of drought frequency and vulnerability with the use of spatial data layers in a GIS environment. Specifically, the physical, human, and infrastructural attributes of the environment and natural processes are characterized to determine the risk effect across each county.

The drought frequency analysis utilized two time scales, depending on the impact sector being investigated. The two time scales were: 3-month and 12-month intervals. Following the recommendations given by the Hawaii Drought Plan, the three drought severity levels considered were: moderate, severe, and extreme.

The vulnerability portion of the equation was addressed through a series of intensive examinations of each of the impact sectors through GIS analysis methods and interpretations. The goal is to develop the best case scenario with what GIS data are available to identify the potential locations of vulnerabilities across each county and sector. Working assumptions were delineated (see Section 4), and a vulnerability analysis was conducted to determine to what extent a county's public water supply, agriculture and commerce, and environment and population were vulnerable to drought or the drought induced effects, i.e., wildland fires. Based on these scenarios, a key component to the vulnerability analysis was the inclusion of a precipitation level in terms of a tercile categorization measure (i.e., low, medium, and high). Low rainfall locales were assumed to be more vulnerable to drought risk than those areas within high or medium rainfall zones. It should be noted that the term "low" rainfall is not in an absolute sense but rather as a relative measure changing across counties based on the distribution of median rainfall values at each gage.

5.2 WORKING ASSUMPTIONS

Assuming that each county is affected consistently by drought within each sector, results of the drought risk analysis based on the SPI time scales of 3 or 12 months should be subject to the same interpretations for each county by sector. Thus, the criteria determining the levels of risk should remain consistent across the state. Although all sectors were analyzed for moderate, severe, and extreme drought stages, evaluating risk to each sector requires assumptions as to what severity level best illustrates the risk to the particular sector.

Focusing on three impact sectors, it was determined that the vulnerability within each sector is based on a particular sector's ability to cope with precipitation deficits. Although all sectors are very much impacted by long periods of low precipitation conditions, some sectors are highly sensitive to short-term precipitation deficits. For example, in the Agriculture Sector, crops that are not irrigated are sensitive to changes in precipitation levels. Of course, this is also dependent on plant species and other factors. A short-duration drought event would generally cause reduced crop yields and livestock forage losses. For this study, a 3-month SPI was deemed as the adequate measure of drought conditions for the agriculture sector. The Water Supply Sector tends to be impacted by longer periods of drought. In this case, the 12-month duration is applied because the response of ground water levels to drought can be delayed by several months to more than a year. At this time scale, potable water supply sources begin to diminish and water conservation measures must be imposed. Hence, for the water supply sector, a 12-month SPI is used to evaluate drought frequency. Focusing on wildland fires, short-term shortages of precipitation are noticeably reflected in the relative greenness of vegetation, thus increasing the opportunity for fires to ignite much more readily and spread much quicker. Any lack of precipitation in the long-term will only exacerbate the situation. For this particular sector, it is desirable to examine drought frequency at both 3-month and 12-month SPI intervals because of the sector's sensitivities to changes in precipitation and overall soil moisture at different time scales.

5.3 DROUGHT RISK ASSESSMENT

5.3.1 COUNTY OF HAWAII DROUGHT RISK ASSESSMENT

5.3.1.1 WATER SUPPLY SECTOR

Figure 5.1 shows the spatial distribution of moderate drought based on a 12-Month SPI overlay on the water supply layer for the County of Hawaii. The percentages of drought frequency are represented as contour lines with those values greater than 16 percent shown in dark blue. At this moderate drought stage, the areas where the 12-month SPI shows a relative maximum (i.e., ≥ 16%) are found on the west Hawaii covering Kohala, south Kohala, and north Kona. It is noteworthy to mention that the latter two areas are also characterized by low median annual rainfall, and the high frequency of drought occurrences in the last 30 years has threatened the Water Supply sector. Another troubling region is the southern tip of the island where high drought frequency is compounded by low rainfall and the lack of public water service areas. In the event of a prolonged drought (e.g., ≥ 12 months), the choices of means for supplying water to local inhabitants are both limited and costly. As previously mentioned in Chapter 4, there are varying degrees of vulnerability associated with the different integrated water systems. Reiterating what was said, integrated water systems that are supplied by groundwater are considered to be less vulnerable than integrated systems that are supplied by surface water sources. The rationale is based on surface water system vulnerability to hydrological drought. The Hawaii County populations in South Kohala and Pahala are two such areas in the State of Hawaii that are served by surface water systems. Given a 12-month SPI with a high relative maximum for these areas, they are at increased drought risk.

The assessment of the severe drought stage is also based on a 12-month SPI. Because the expected frequency of this stage is substantially less than moderate drought (Table 3.1), the contour line for highlighting drought frequency is now reduced to 8% and above. As shown in Figure 5.2, a large area of high frequency (i.e., 8 to 16%) is found in the southern portion of the island, extending from south Kona, Kau, to Hawaii Volcanoes National Park. This area also features low rainfall and limited public water services. Just as in the moderate drought stage (Figure 5.1), the North Kona coast area exhibited a high frequency of severe drought occurrence in the past 30 years (Figure 5.2). Other notable regions that experienced a high frequency of severe drought occurred near Waipio Valley, the border of Hamakua and Hilo districts, and the Puna district. However, the first two districts have high mean annual rainfall and may therefore be less vulnerable to severe drought impacts in terms of water supply problems.

For the extreme drought stage, the drought frequency contour begins at 4% (Figure 5.3). The frequency of extreme drought is high in North Kona, however the South Kohala and Pahala systems are served by private water sources (Figure 5.3). Other areas of high drought frequency include the windward slope of the Kohala and Hamakua districts, and the southwestern corner of Kau. The latter two areas are at risk to drought because of the low mean annual rainfall in the area, and lack of water service areas.

5.3.1.2 AGRICULTURE AND COMMERCE SECTOR

Figure 5.4 displays the spatial distribution of moderate drought based on a 3-month SPI overlaid on the agricultural sector's vulnerability assessment for the Island of Hawaii. The regions where drought frequency is higher than 8% are shown in dark blue. A large area of relatively high drought frequency (8 to 12%) is concentrated along the northern slopes of Kohala and Hamakua, of which the latter is marked by pasture land with low rainfall. Another area of concern is Kona. Again, low rainfall together with high frequency of moderate drought (8 to 16%) is not desirable for agriculture. The coastal area of Puna experienced a high frequency of moderate drought but the lack of agricultural data precludes risk assessment.

A relatively high frequency of severe drought (4 to 8%) based on a 3-month SPI occurs largely on the west coast extending from north Kona to south Kona and Kau (Figure 5.5). These areas are known to have low rainfall and host various water-sensitive agricultural activities (e.g., macademia nuts, coffee). A second area of concern is the leeward coast in the Puna district. Because of its low rainfall, the high percentage of severe drought occurrence (8%) from historical rainfall data suggests that the coast of Puna may be undesirable for agriculture.

For the extreme drought stage (Figure 5.6), the pattern is similar to the other two stages shown in Figs. 5.4 and 5.5. Areas with a high drought frequency and low mean annual rainfall are identified in Kona, south Kau, and the coast of Puna.

5.3.1.3 ENVIRONMENT, PUBLIC HEALTH AND SAFETY SECTOR

For this sector, we are concerned with wildland fire. In examining the risk of drought to this sector based on the vulnerabilities and the 3-month SPI interval, it appears that at moderate (Figure 5.7), severe (Figure 5.8), and extreme drought (Figure 5.9) stages, the risk is minimum. There is no overlap between the vulnerable areas with the relative maximum drought frequency (≥ 8%) generated by the SPI. One area in Kona is of concern because of its high drought frequency (8 to 12%), low annual rainfall, and community at risk from fire.

Compared to the 3-month SPI, the 12-month interval scenarios describe different situations. With higher percentages of drought at the moderate stage, between 16 and 32%, areas in the Kohala region, near Waikoloa, coincide with past wildland fires that have occurred in this low rainfall area (Figure 5.10). At the severe stage for the 12-month interval (Figure 5.11), the area of relatively high frequency in Kona coincides partially with past wildland fire locations, but not to the extent observed in the moderate stage (Figure 5.10). In the case of extreme drought (Figure 5.12), although the high percentage (≥ 8%) drought frequency zones cover a large portion of the Kona district, which is a low rainfall area and coincides with a large "Community at Risk," it does not coincide with past wildland fires. Hence, the risk of drought at the extreme stage is not as significant as the risk at the severe or moderate drought stage.

5.3.1.4 SUMMARY OF RESULTS FOR THE COUNTY OF HAWAII

The risk of drought impact on the three sectors within the County of Hawaii is similar in terms of spatial variation. Most of the areas of concern are on the western side of the island, coinciding with low rainfall zones. What differs between each sector is the stage (moderate, severe, or extreme) where drought risk may produce the most significant impacts. For the water supply sector, all stages produce significant risk on the western side of the island. The southern part of the island is also vulnerable to drought risk. The potential risk to this sector is clearly illustrated by applying the 12-month SPI.

In terms of the agriculture and commerce sector, again the western side of the island is at most risk, but the severe drought stage seems to coincide best with low rainfall areas on the west and southwest ends of the island, where various kinds of agricultural activities thrive. The use of a 3-month SPI shows well the potential risk to this sector.

For the environment, public health and safety sector, the 3-month drought interval does not coincide with historical wildfire burn areas. That is, there appears to be no clear overlap between high drought frequency percentages and past wildland fire locations. However, at the 12-month interval, the moderate drought stage in conjunction with the vulnerability analysis for this sector provides the best means of evaluating the risk.

5.3.2 COUNTY OF MAUI DROUGHT RISK ASSESSMENT

5.3.2.1 WATER SUPPLY SECTOR

As explained in Section 4, it was made clear that the vulnerability of the water supply sector was incumbent on several factors: low rainfall, a lack of public water service, and a significant population density in the area. In examining the 12-month SPI of moderate drought with the results of the vulnerability analysis for Maui's water supply sector (Figure 5.13), one notes several locations where the relative maximum (≥ 16%) coincides with the vulnerable water supply sector areas. The entire central region (Kula, Makawao, Kahului and Wailuku) and the Lahaina coast and Hana are within this relative maximum zone. These areas meet several of the vulnerability criteria. The greater part of Maui's population lives within these low rainfall regions. Although there appears to be adequate public water service, this may be misleading with the increasing tourist and residential developments in the region, compounded with the low rainfall in this region. Furthermore, Kula and Makawao are served by surface water systems originating in East Maui, thus increasing vulnerability. Risk from even a moderate drought could produce pronounced impacts effecting the population. Molokai and Lanai, except for Central Lanai, do not appear to be at risk to the same degree as Maui in terms of a moderate drought event.

Again, as stated in Chapter 4, having an integrated water system does not necessarily equate to a lack of vulnerability from the effects of a drought. There are different types of integrated water systems and differing vulnerability associated with each. Integrated water systems that are composed primarily of surface water sources are much more vulnerable to the effects of a hydrological drought than those that draw on ground-water. Saying this, areas on Maui, like Kula and Makawao that are serviced by surface water sources have a higher vulnerability than those areas that are serviced by ground-water sources. This vulnerability compounded with the high relative maximum (≥ 16%) over a 12-month period verifies the extent of drought risk in the area of Kula and Makawao.

For the severe drought stage (Figure 5.14), most of the high frequency areas are located in regions of medium to high rainfall or are less populated. Hence, one can assume that the risk to the water supply sector is not as great compared to a moderate stage drought. However, the Kula area and Hana are still at risk. The eastern and western ends of Molokai and Central to Southern Lanai also saw a higher frequency of severe drought occurrence (≥ 8%) in the past 30 years. For extreme drought (Figure 5.15), the highest frequency areas on Maui are located in regions of normally high rainfall, which lowers the overall risk of drought impact.

5.3.2.2 AGRICULTURE AND COMMERCE SECTOR

The results associated with a 3-month SPI moderate drought (Figure 5.16) do not show significant risk on the island of Maui. On Lanai, the central intensive agriculture lands, which already receive low rainfall, are at risk. For Molokai, a large percentage (8%) of the moderate drought zone is located on the western side of the island, which is normally the dry side of the island. With extreme vulnerabilities due to the low rainfall and increased odds of being impacted by a moderate drought, the extensive and intensive agriculture lands in West Molokai are at great risk. Beyond the moderate stage, the severe drought stage does not seem to pose much risk based on the results presented in Figure 5.17. The exception is Southern Lanai, which again has a relative higher risk of impact. At the extreme drought stage (Figure 5.18), there is even less of a risk of impact for all three islands. Even Lanai does not appear to be at any significant extreme drought risk.

5.3.2.3 ENVIRONMENT, PUBLIC HEALTH AND SAFETY SECTOR

Based on the 3-month SPI for moderate drought (Figure 5.19), there is minimal risk on all the islands. Although there are vulnerable areas that coincide with the 8% drought frequency contour on Maui (near Lahaina) and Lanai (near Lanai City), these are very small in comparison to other fire areas across the county. Central Molokai, from Kaunakakai to Molokai Airport, has been consumed by past fires and is within a low rainfall zone. This is also the region of a relatively high drought frequency (≥ 8%). Hence, the risk factor should be greater.

At the severe drought stage for a 3-month interval, the risk to Molokai is no longer as great, but at this stage the most vulnerable location is on Maui, between Olowalu and Maalaea (Figure 5. 20). This “Community at Risk” receives very little amounts of rainfall, has a higher drought frequency (≥ 4%), and has been ravaged by past wildland fires. In examination of extreme drought for a 3-month interval (Figure 5.21), there appears to be no areas that are at great risk from fire.

Relative to the 3-month SPI (Figure 5.19), the 12-month interval for moderate drought presents a different scenario and the risk to this sector is much more obvious (Figure 5. 22). The areas of the Kula region (from the top of Haleakala to the eastern slopes of the West Maui Mountains) are subject to high drought frequency (≥ 16%) and vulnerable locations, thus increasing the risk of impact from drought. South-Central Molokai has had occasional wildfires, but the frequency of moderate drought is not high there. At the severe drought stage (Figure 5.23), the Kula region of Maui is still highlighted as being at great risk. Wildland fires on Molokai and Lanai do not overlap with high drought frequency regions. For the extreme stage (Figure 5.24), the Kula region still stands out as an area of great risk to drought impact.

5.3.2.4 SUMMARY OF RESULTS FOR THE COUNTY OF MAUI

For Maui, the area of greatest risk to the public water supply and environment, public health and safety sectors is within the Kula region. This was shown to exist throughout all stages from moderate, severe, and extreme drought. The 12-month SPI moderate drought contours are of note as high frequency areas coincide spatially with intensive agriculture areas, particularly in central Maui. In terms of the risk of drought to Maui’s Water Supply Sector, the importance of drought risk to the areas of Kula and Makawao should be reiterated. Given the vulnerability of integrated surface water source systems to hydrological drought and Kula and Makawao’s location in areas of high drought frequency, they are at risk during all stages of severity (moderate, severe, and extreme) at the 12-month drought duration. However, given a low mean annual rainfall and its remote location and limited accessibility, the collective effect of a high frequency of both moderate and severe drought suggests that Hana is more vulnerable to drought impacts as far as water supply is concerned. The southern area of Lanai is characterized by a relatively high percentage of severe drought frequency and low annual rainfall, posing a great risk to the water supply and environment, public health and safety sectors. The central area of Molokai has a high percentage of drought frequency and is particularly vulnerable to fire hazards. Of concern, for this study, is the analysis of the agriculture and commerce sector for the County of Maui. This analysis did not indicate where the risk may be the greatest. Because this analysis was based on the assumption that conditions and characteristics in examining each sector remained constant across each county, there was little room for individual adjustments for each county, let alone each island within a county. In reality, this may not be the case; each island would have its own physical characteristics that may have to be taken into account if any detailed examination of risk is to be conducted.

5.3.3 CITY AND COUNTY OF HONOLULU DROUGHT RISK ASSESSMENT

5.3.3.1 WATER SUPPLY SECTOR

The City and County of Honolulu has an extensive integrated public water system that provides water to nearly the entire island. Therefore, it may be difficult to envision any great risk to drought impact on the public water supply sector. Nevertheless, the water supply, which comes from groundwater sources, is not unlimited, so the risk to some impacts is very plausible. For moderate drought based on 12-month SPI (Figure 5.25), the relative maximum drought frequency (≥ 16%) captures the area of central Oahu, including Mililani and Waipio. Although this area is not totally within the low rainfall zone, it is characterized by an increasing population with associated water demands. Other areas of moderate risk that are highlighted (16%) are the areas near Salt Lake and central Honolulu. These areas are not growth regions, but do exhibit high populations, and are within the medium rainfall zones.

At the severe stage (Figure 5. 26), a very large region extending from Central Oahu to the North Shore (Haleiwa to Kuilima) is noted with a relatively high percentage of drought (≥ 8%). Most at risk are again the areas of Central Oahu where the population is growing and mean annual rainfall is low to medium. Going from a severe drought to an extreme drought produces a different outcome as to where the "at risk" water supply sector is located. For the extreme stage (Figure 5. 27), drought risk is no longer situated along the central portion of Oahu, but has moved to the low rainfall regions of Ewa and Kaaawa. It is useful to note that during a moderate and severe drought stage on Oahu, areas at risk are not necessarily of low rainfall, but areas that exhibit increased drought frequency and high populations. At the extreme stage, risk is a factor of low rainfall, high populations, and increased drought frequency.

5.3.3.2 AGRICULTURE AND COMMERCE SECTOR

With increased urbanization, the remaining productive intensive and extensive agriculture lands on Oahu are limited. Most of the lands that are still in agriculture production and are vulnerable to drought impacts are located in the central region from Kunia to Haleiwa. For the moderate stage, the greatest risk areas are the intensive and extensive agriculture lands receiving low to medium rainfall from the Ewa Plain through Central Oahu, north to Helemano (Figure 5. 28). An examination at the severe drought stage confines the area at risk to the Kunia region (Figure 5. 29), which includes more lands of intensive agriculture than extensive agriculture within low to medium rainfall zones. At the extreme stage (Figure 5. 30), the risk to intensive agriculture has all but disappeared. The risk area has instead shifted from Central Oahu, as observed in the severe stage (Figure 5. 29) to the medium rainfall extensive agricultural lands above Helemano and Haleiwa during the extreme stage (Figure 5.30).

5.3.3.3 ENVIRONMENT, PUBLIC HEALTH AND SAFETY SECTOR

For moderate drought at a 3-month interval (Figure 5. 31), the only vulnerable location that coincides with the drought frequency range (≥ 8%) occurs in the Waipio/Mililani/Pearl City area where past wildland fires, low rainfall, and known "communities at risk" has made this area very vulnerable to wildland fires. Moving to a severe drought stage (Figure 5. 32), once again the high risk area for this sector is located in the Waipio/Mililani area. At the extreme drought stage (Figure 5. 33), the former area no longer stands out as an area of risk concern. Kaaawa and Pupukea are marked by a relatively high drought frequency (≥ 4%), but rainfall is in the medium to high range so the risk to drought impact may not be high. Relatively speaking, although a region near Kaena Point is highlighted as a potential risk area, the population in this region is nonexistent. However, because of the lack of access into the region, extremely low rainfall, vegetation type in this region, and frequency of past wildfires, this region is identified as a risk area.

From the analysis of the moderate and severe drought stages based on 12-month interval (Figs. 5.34 and 35), the same region of Waipio/Mililani is a high risk area. Again, this is a function of both the vulnerability of that location for this sector and the relative high drought frequency. It should be noted that this region remains consistently at high risk for both a 3-month and a 12-month interval drought. For the extreme stage (Figure 5.36), the potential risk area is in the Pearl City/Waipahu area because of the combined effects of low rainfall, high populations, increased drought frequency, and the identified communities at risk to wildfire.

5.3.3.4 SUMMARY OF RESULTS FOR THE CITY AND COUNTY OF HONOLULU

To summarize, the risk to the City and County of Honolulu is not like that of the other counties. Although a greater proportion of the State's population lives within Oahu, drought vulnerability to the extent found on the islands of Hawaii and Maui does not exist on Oahu. With an integrated water system, a service area that covers the majority of the island, and groundwater as the primary source for potable water, the public water supply sector is not as vulnerable to minor drought conditions. If a severe drought persists for more than one or two years, the ground-water supply would be depleted to a large extent and the entire island would be affected despite the extensive ground-water integrated public water system. Other problems include the growing population occurring in the leeward or central portion of the island where rainfall is low.

In terms of risk to the agriculture and commerce sector, although there is some risk within the central portion of the island near Kunia for the moderate and severe drought stages, the City and County of Honolulu does not have as many lands devoted to this sector as compared to other islands. Hence, there is a need for refinement of the assumptions and methodology used to identify and quantify risk to account for the differences from county to county within each of the sectors.

The environment, public health and safety sector is somewhat different from the other two sectors. Although wildland fires can be induced by the symptoms of drought, a fire usually is started through man's influence. Still, based on the analysis, the area near the Mililani/Waipio region seems to be at high risk for the moderate and severe drought stages. This area is in an urban/wildland interface where the highway passes through acres of open scrub land. Hence, a fire poses a threat to the developed land and public transportation system in the area.

5.3.4 COUNTY OF KAUAI DROUGHT RISK ASSESSMENT

5.3.4.1 WATER SUPPLY SECTOR

As explained previously in Section 4, the densely populated areas on Kauai are serviced by the public water system, this makes the vulnerability very minimal. This being the case, one would assume that risk would also be minimal but this may not be true in reality. Keep in mind that the service area is only a general feature. It is not designed to provide an exact measure of service extent, but rather provide a broad view of water coverage.

For the moderate drought based on 12-month interval, one drought prone region extends from the Hanalei Coast through Alakai Swamp to the south-central mountainous regions (Figure 5.37). Although rainfall is low and drought frequency is high (≥ 16%), these regions are not populated so the risk from drought is low. The same can be said for another region in northeast Kauai where the drought frequency reaches 16% or more. During a severe drought stage (Figure 5.38), the greatest risk area to the water supply is located in the Koloa region because this region is in a low rainfall zone, has a sizable population, and has an increased drought frequency (8 to 12%). Although the water service area does not seem to be lacking in this area, but this is only from a regional perspective, hence a zoomed in localized perspective may say otherwise. Other areas where drought frequency is high include Anahola (≥ 12%), and to a lesser degree (8%) in Kapaa, Wailua, Lihue, and Poipu. At the extreme stage (Figure 5.39), the greater areas of Kapaa, Lihue, and Poipu are again affected by increased drought frequency. Not only are these areas within low rainfall zones, but they are heavily populated. Other areas that are at risk are located along the North Shore from Hanalei to Anahola. At this drought stage, the local population as well as the tourist industry in the areas of Princeville and Poipu suffers from the impact to the water supply.

5.3.4.2 AGRICULTURE AND COMMERCE SECTOR

At the moderate stage (Figure 5.40), there are several areas that are at risk within the agriculture and commerce sector. These areas include the interior intensive and extensive agricultural lands in Waimea, the coastal intensive and extensive agricultural lands between Poipu and Lihue, and the coastal intensive agricultural lands of Anahola. All these areas are in low rainfall zones coinciding with maximum drought frequencies (≥ 8%) at the 3-month interval. As the drought stage increases to a severe drought (Figure 5.41), the area of higher frequency moves to the north interior of the island where there are relatively high amounts of rainfall. Because most agricultural lands are close to the coast, the higher frequency of drought found in the interior north does not add to the risk of impact to this sector. However, there are some coastal agricultural lands that may be at risk during a severe drought condition. These include the intensive agricultural lands of Anahola and Kekaha/Mana, with the latter being located in low rainfall zones compounded with a relative maximum in drought frequency (≥ 4%). During the extreme drought stage (Figure 5.42), the risk area is confined to the intensive and extensive agricultural lands southwest of Lihue that receive low rainfall and maximum drought frequencies (≥ 4%).

5.3.4.3 ENVIRONMENT, PUBLIC HEALTH AND SAFETY SECTOR

Based on information of where past wildland fires occurred, Kauai appears to have the least amount of problems with wildland fires. Most of the fires have occurred in the forest reserves of Waimea, away from population concentrations (limited past wildfire data was available). Communities that are at risk from wildland fires on Kauai are located along the coast (Figs. 5.43 to 5.48) and they are usually not in the regions where drought frequency is high. The exception is the Lihue/Poipu and Wailua regions at the severe drought stage (Figure 5.47) and again the Lihue/Poipu/Koloa region at the extreme stage (Figure 5.48). In general, there is no significant overlapping between the drought frequency analysis results and the vulnerability analysis results to determine the level of risk of wildland fire to the population of Kauai. However, this does not mean that there is no threat of wildland fire on Kauai in the future. Although drought conditions are primers for wildland fires, they are not the cause. Most of the time wildland fires are started by humans and tend to occur at the urban/wildland interfaces.

5.3.4.4 SUMMARY OF RESULTS FOR THE COUNTY OF KAUAI

The risk of impact to the County of Kauai from drought can be summarized as follows. Kauai has an extensive water supply system to cover nearly the entire population, but this may be misleading. From the analysis, it was determined that the majority of all the developed lands coincide with low rainfall zones; hence, it would appear that these lands are susceptible to drought risk. Still, only a few of these lands fall in the zones of maximum drought frequency. One area that stands out through the severe and extreme drought stages is the Koloa region. Therefore, one may say that this area is at risk to the water supply sector.

Because the vulnerability of the agricultural lands is high due to the fact that most of these lands are in low rainfall zones, one would expect a greater risk. However, upon examination of the drought risk maps, this is not always the case. In fact, the vulnerable areas that coincided with the high drought frequency regions were very few. One area noteworthy as being at risk, in both the moderate and severe stages, was the Anahola region. Other areas that are concern are located near Lihue.

An examination of the environment, public health and safety sector did not yield any apparent or significant outcomes to determine the relative risk levels to this sector. The exception is a small area in the Lihue/Poipu region at both the severe and extreme drought stages based on the 12-month SPI interval. Thus, the County of Kauai would appear to have little risk in terms of wildland fires. Because wildland fires are induced by drought conditions, there is no clear indicator as to where the greatest risk would occur based solely on drought frequency and low rainfall. One could say that each one of the “Communities at Risk” that are within low rainfall zones and coincide with high drought frequency would be at risk. Without greater knowledge of past wildland fires on Kauai, the assumption of this analysis would not provide information as to the areas at risk.

Figure 5.1 Drought Risk Areas
Water Supply Sector, County of Hawaii
12-Month SPI, Moderate Drought

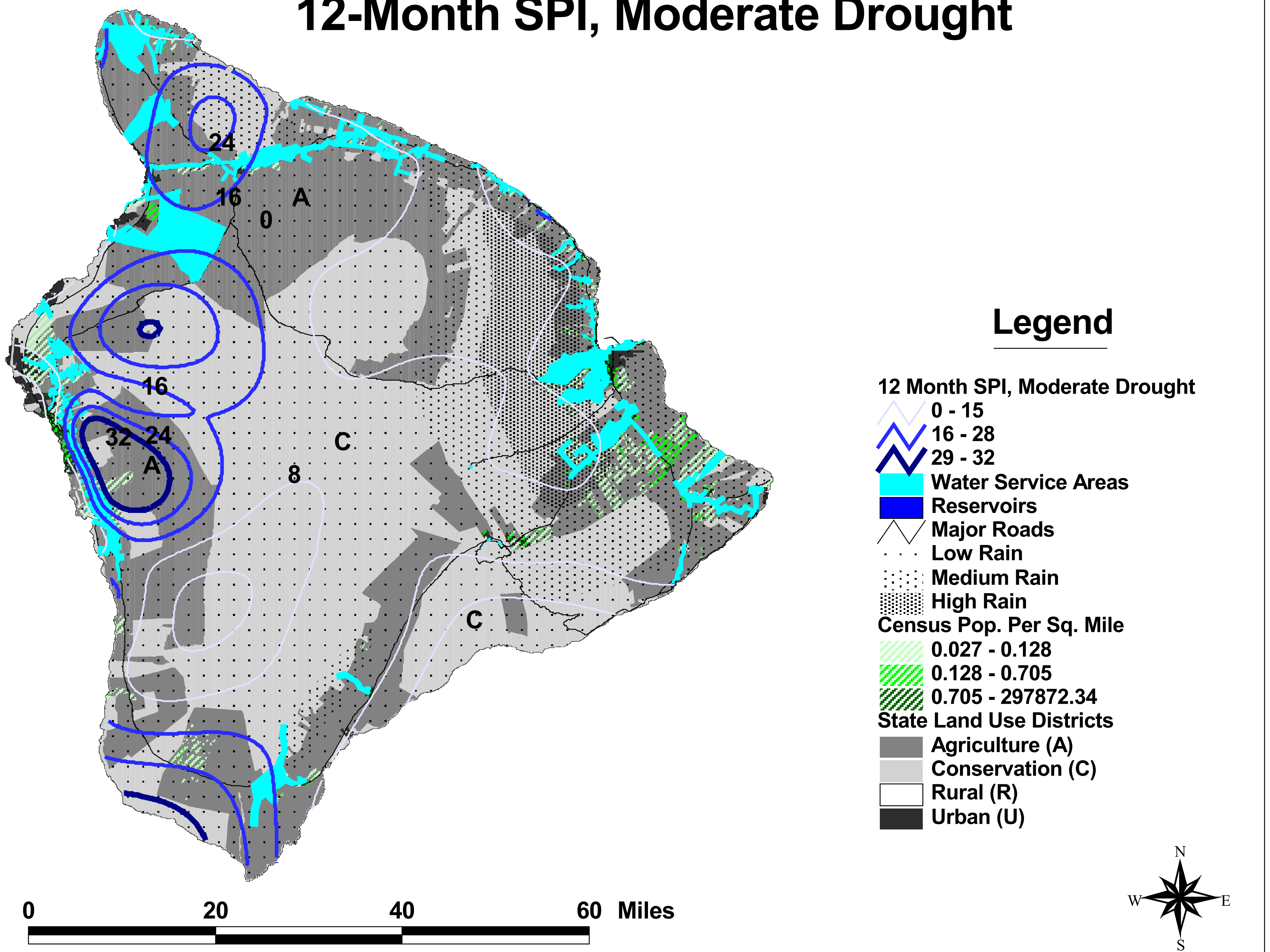
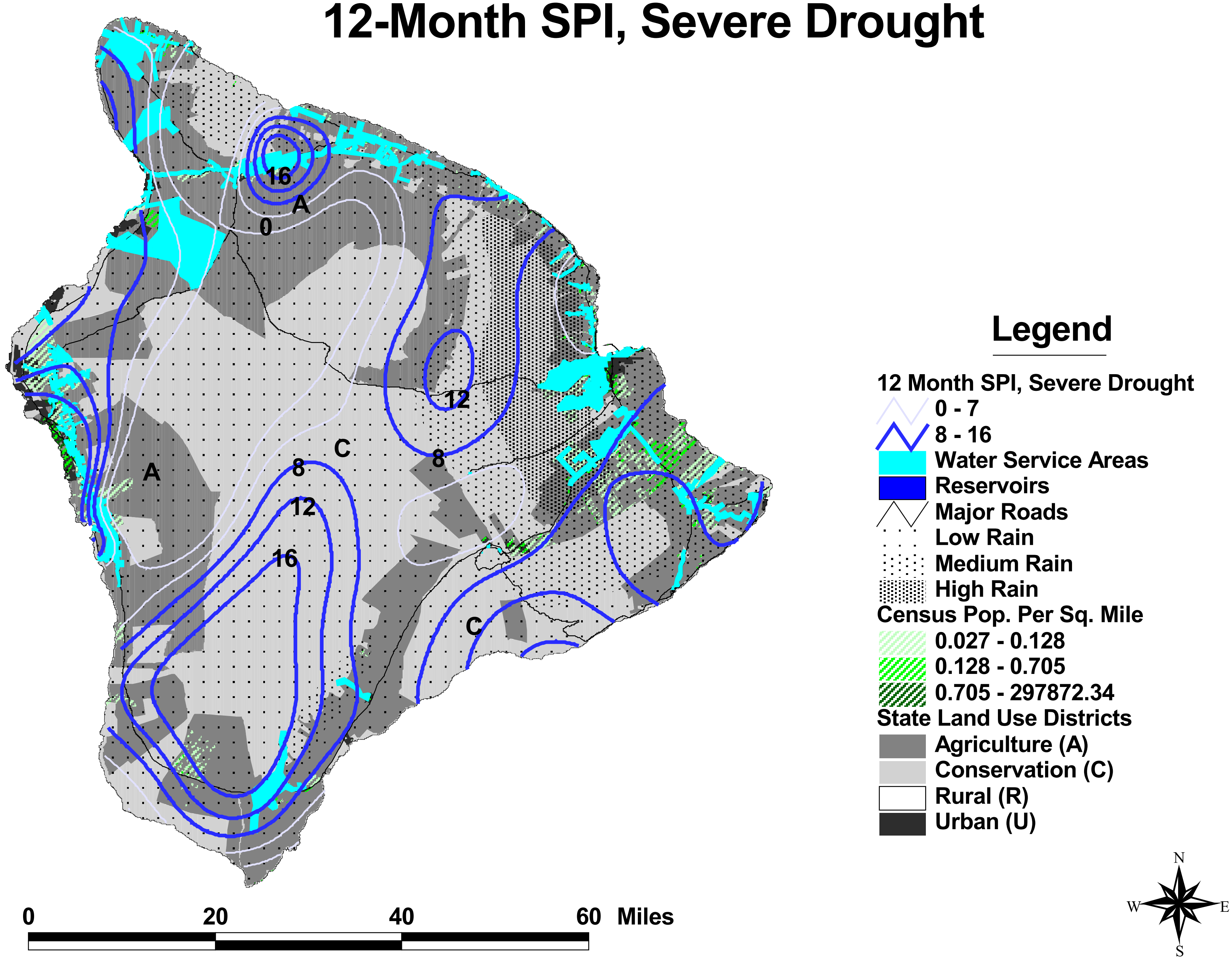


Figure 5.2 Drought Risk Areas
Water Supply Sector, County of Hawaii
12-Month SPI, Severe Drought



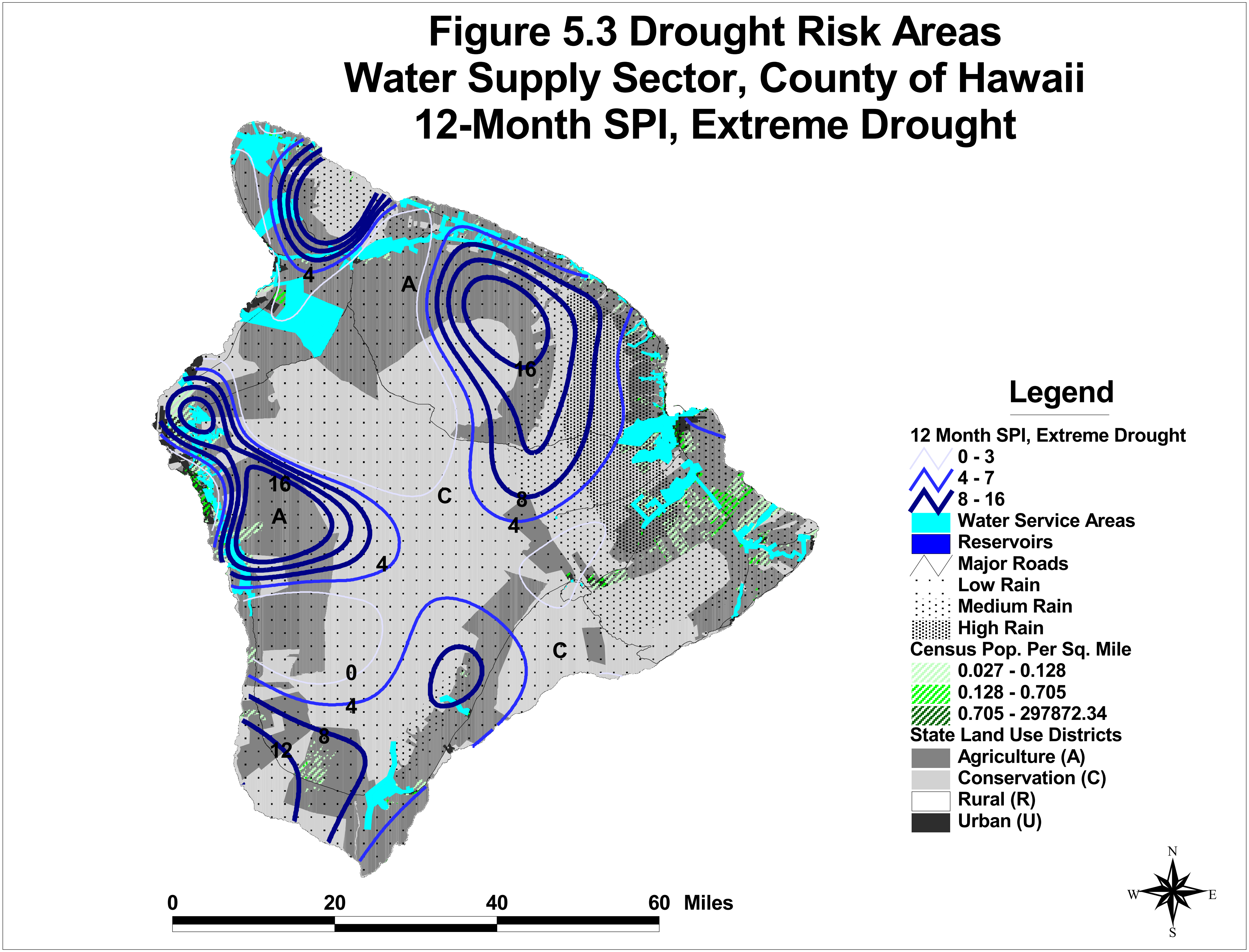


Figure 5.3 Drought Risk Areas
Water Supply Sector, County of Hawaii
12-Month SPI, Extreme Drought
Legend
12 Month SPI, Extreme Drought
0 - 3
4 - 7
8 - 16
Water Service Areas
Reservoirs
Major Roads
Low Rain
Medium Rain
High Rain
Census Pop. Per Sq. Mile
0.027 - 0.128
0.128 - 0.705
0.705 - 297872.34
State Land Use Districts
Agriculture (A)
Conservation (C)
Rural (R)
Urban (U)
0
20
40
60
Miles
N
S
E
W

Figure 5.4. Drought Risk Areas
Agriculture Sector, County of Hawaii
3-Month SPI, Moderate Drought

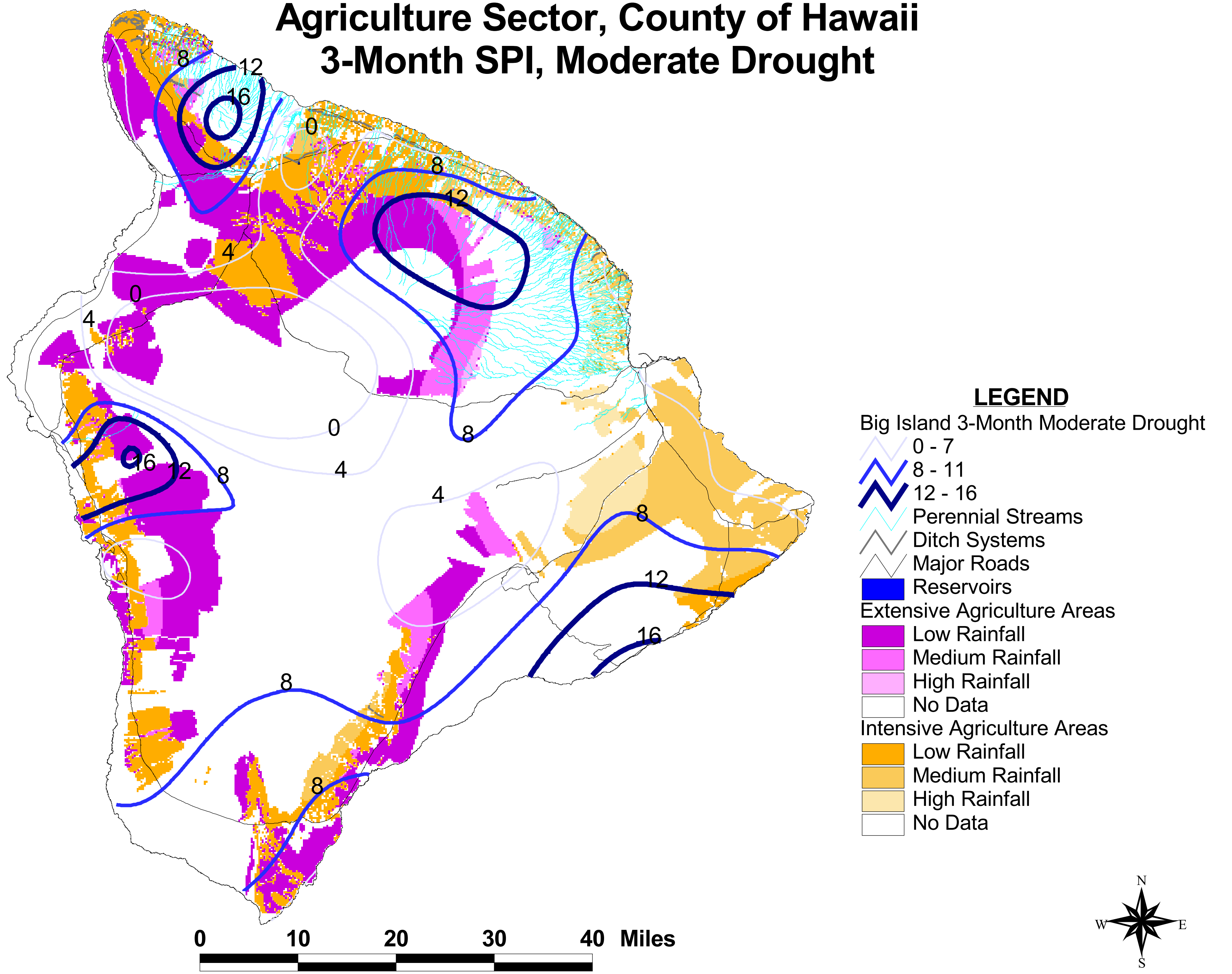


Figure 5.5. Drought Risk Areas
Agriculture Sector, County of Hawaii
3-Month SPI, Severe Drought

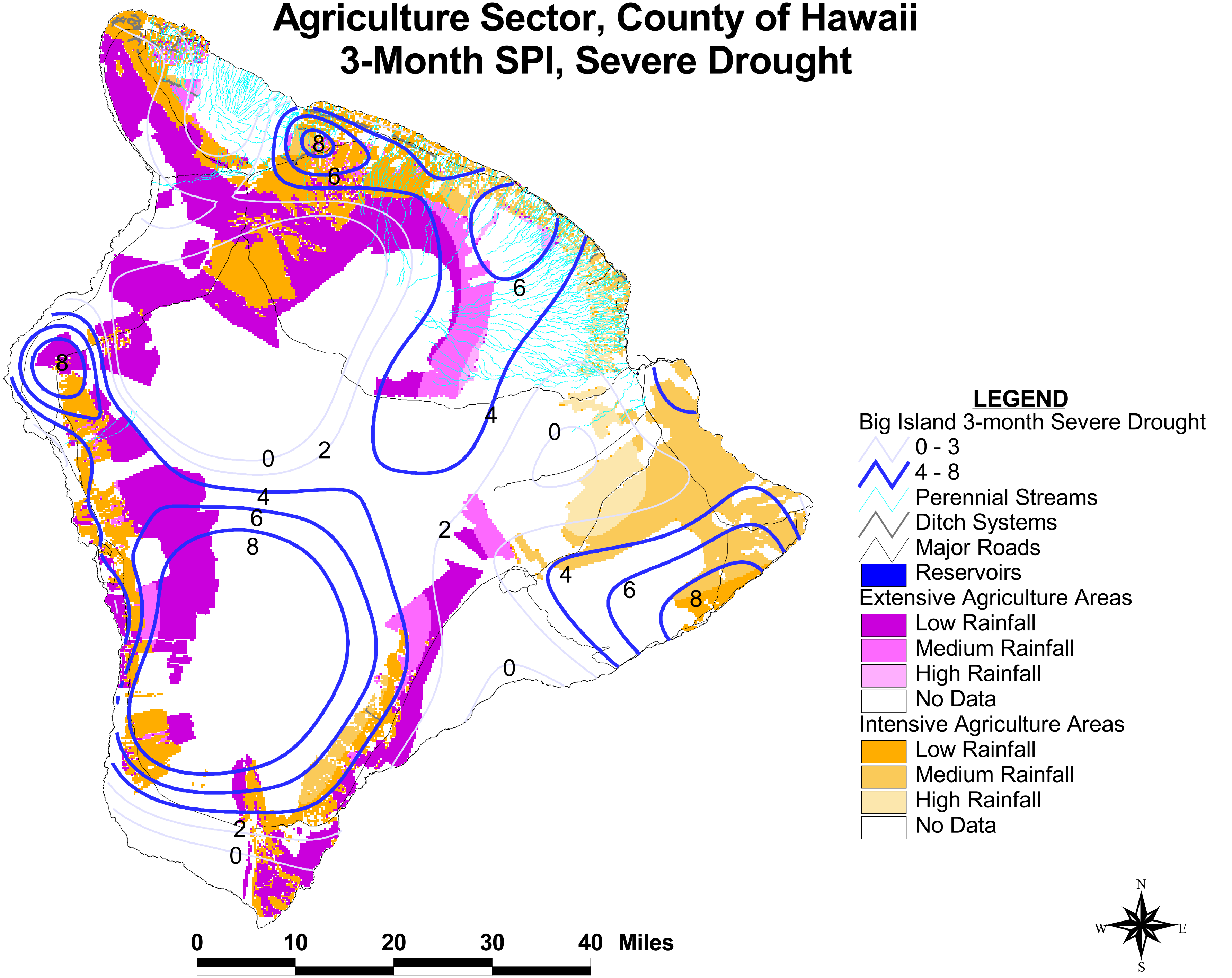


Figure 5.6. Drought Risk Areas
Agriculture Sector, County of Hawaii
3-Month SPI, Extreme Drought

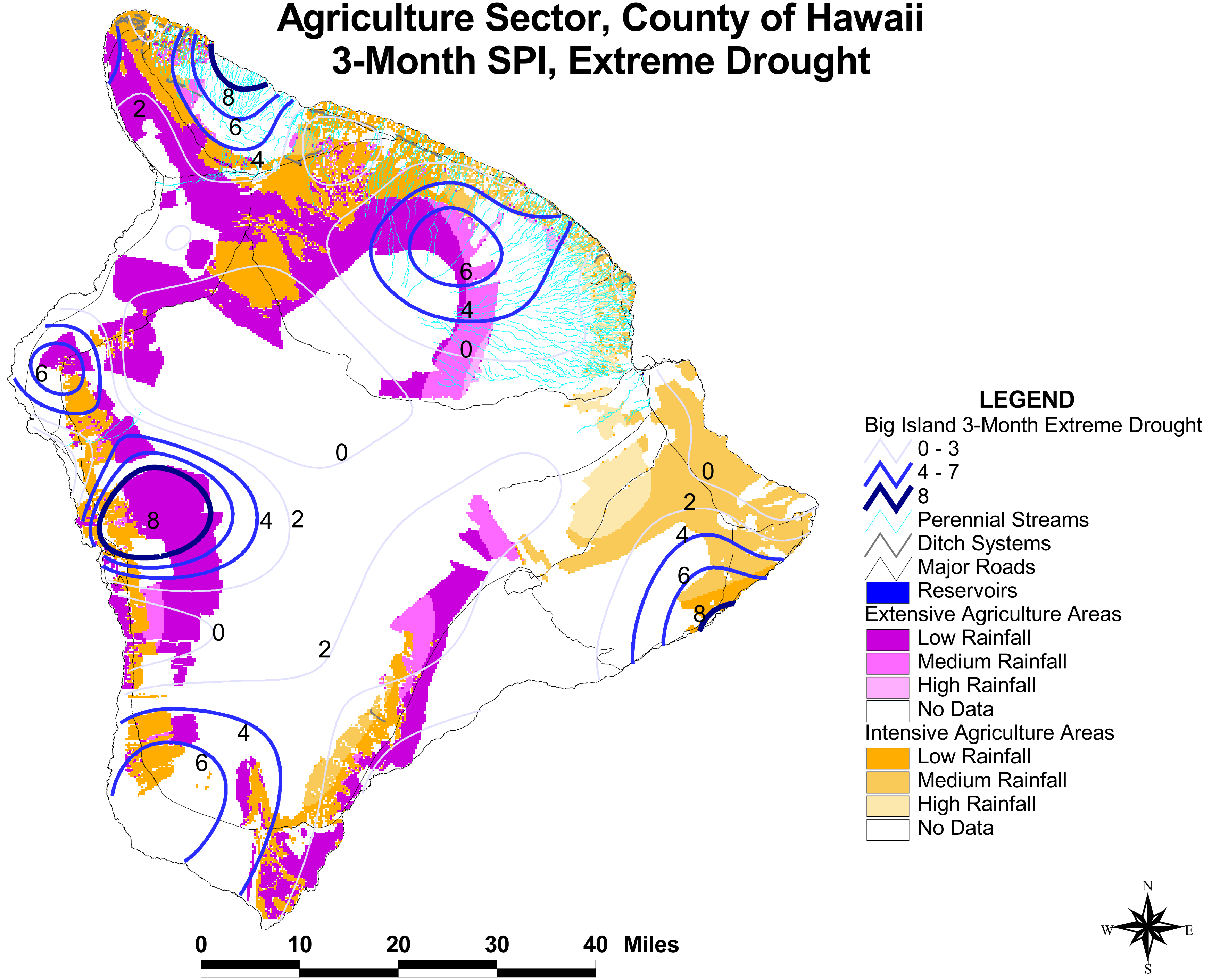


Figure 5.7. Drought Risk Areas
Environment, Public Health, and Safety Sector, County of Hawaii
3-Month SPI, Moderate Drought

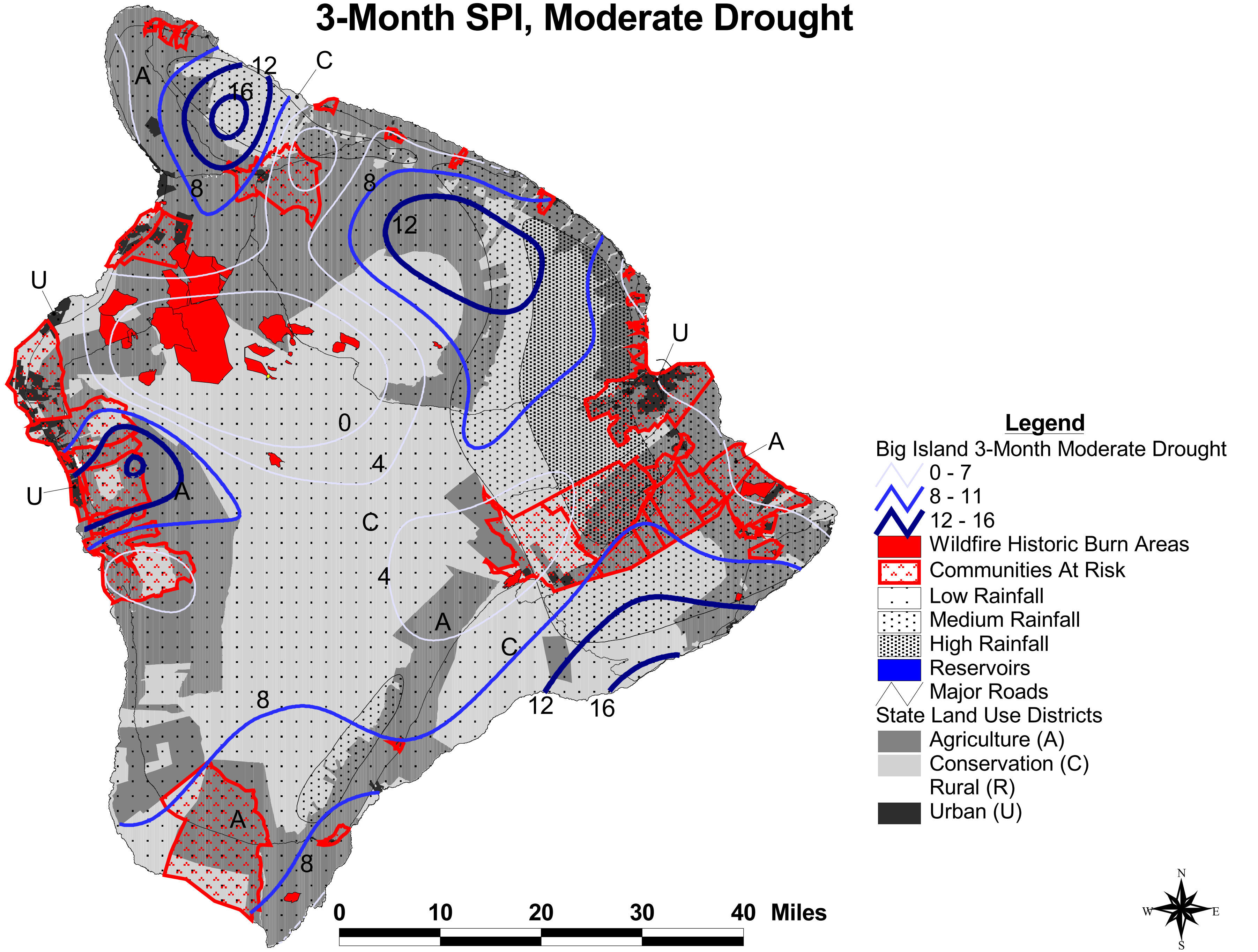


Figure 5.8. Drought Risk Areas
Environment, Public Health, and Safety Sector, County of Hawaii
3-Month SPI, Severe Drought

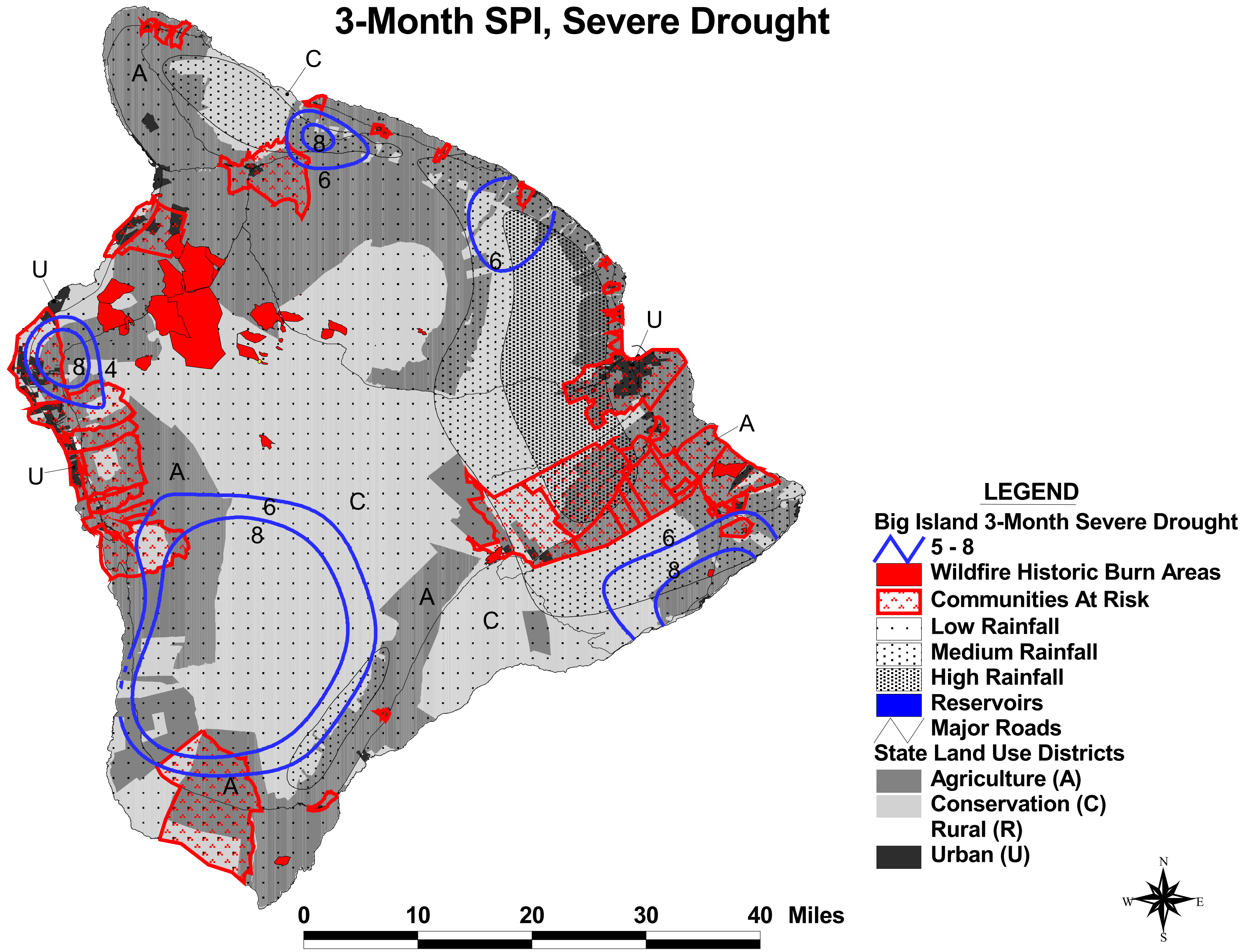


Figure 5.9. Drought Risk Areas
Environment, Public Health, and Safety Sector, County of Hawaii
3-Month SPI, Extreme Drought

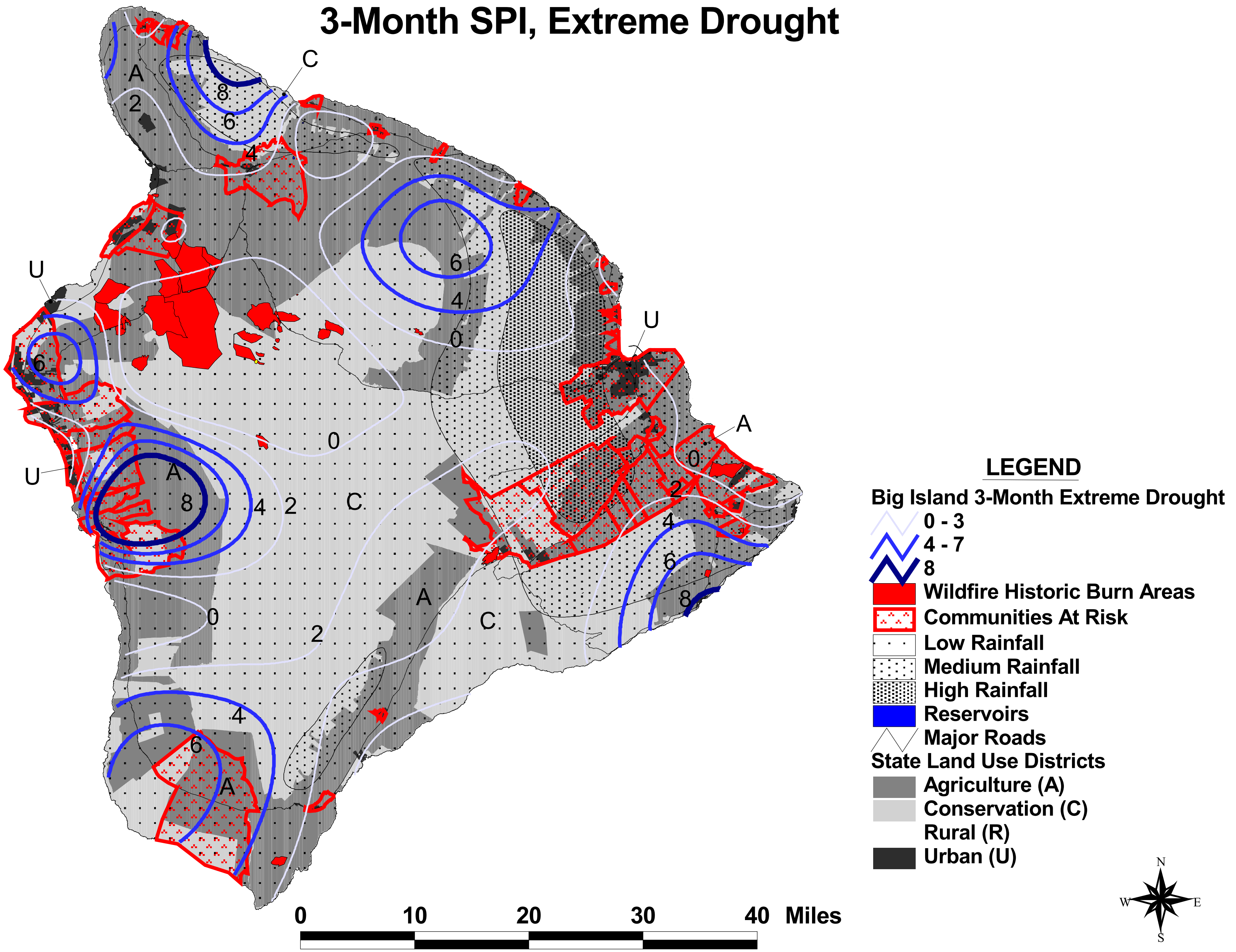


Figure 5.10. Drought Risk Areas
Environment, Public Health, and Safety Sector, County of Hawaii
12-Month SPI, Moderate Drought

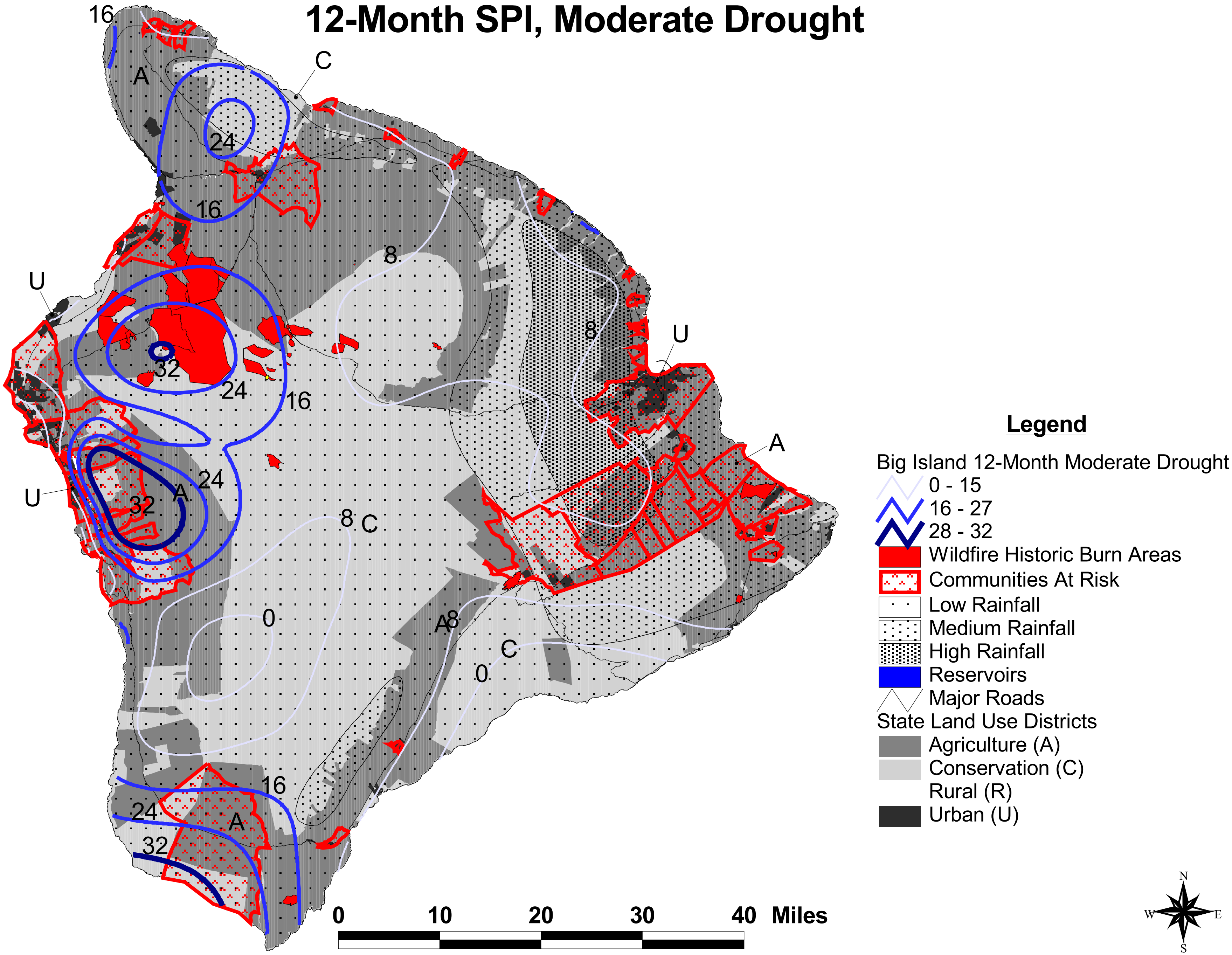


Figure 5.11. Drought Risk Areas
Environment, Public Health, and Safety Sector, County of Hawaii
12-Month SPI, Severe Drought

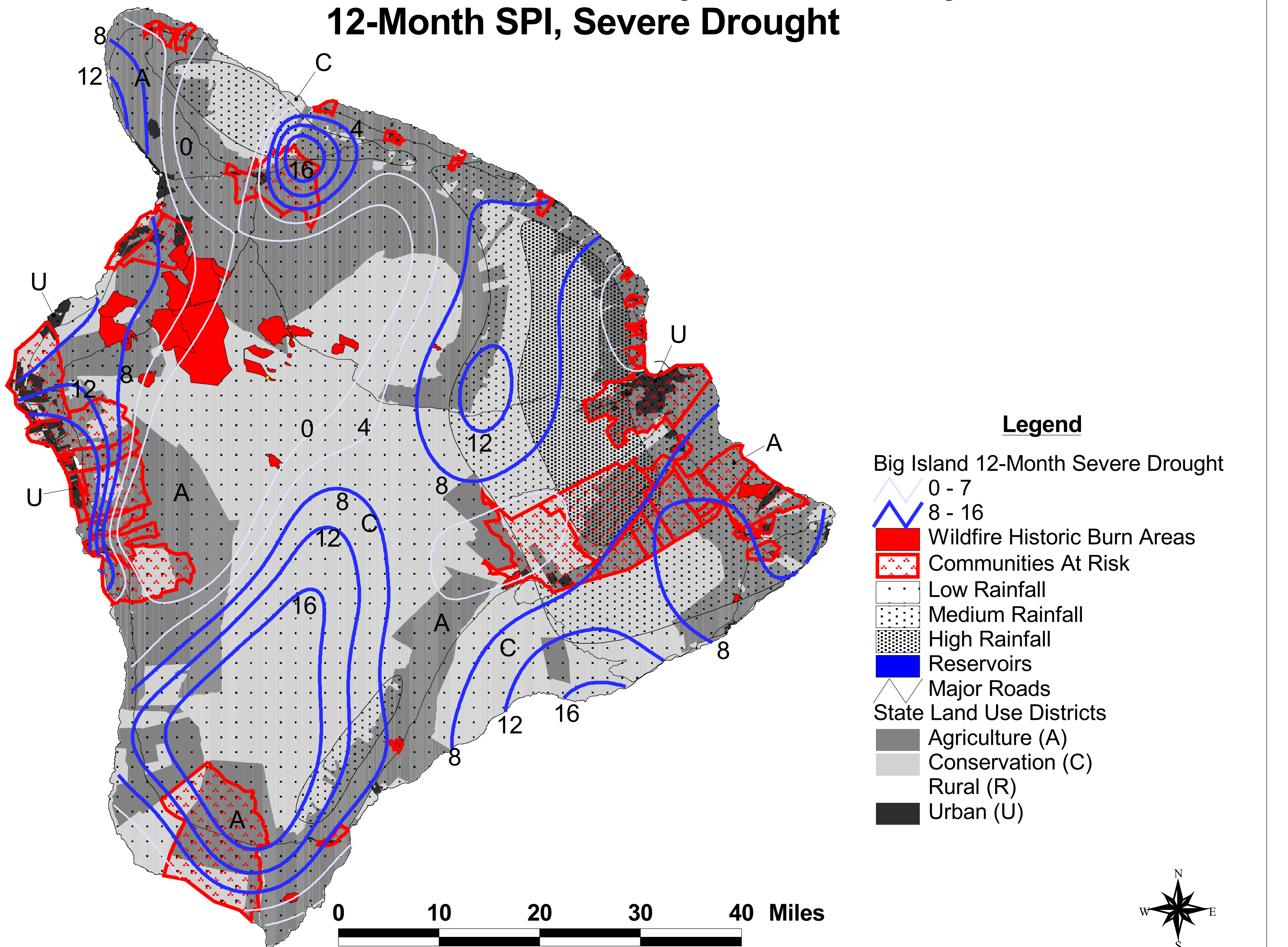


Figure 5.12. Drought Risk Areas
Environment, Public Health, and Safety Sector, County of Hawaii
12-Month SPI, Extreme Drought

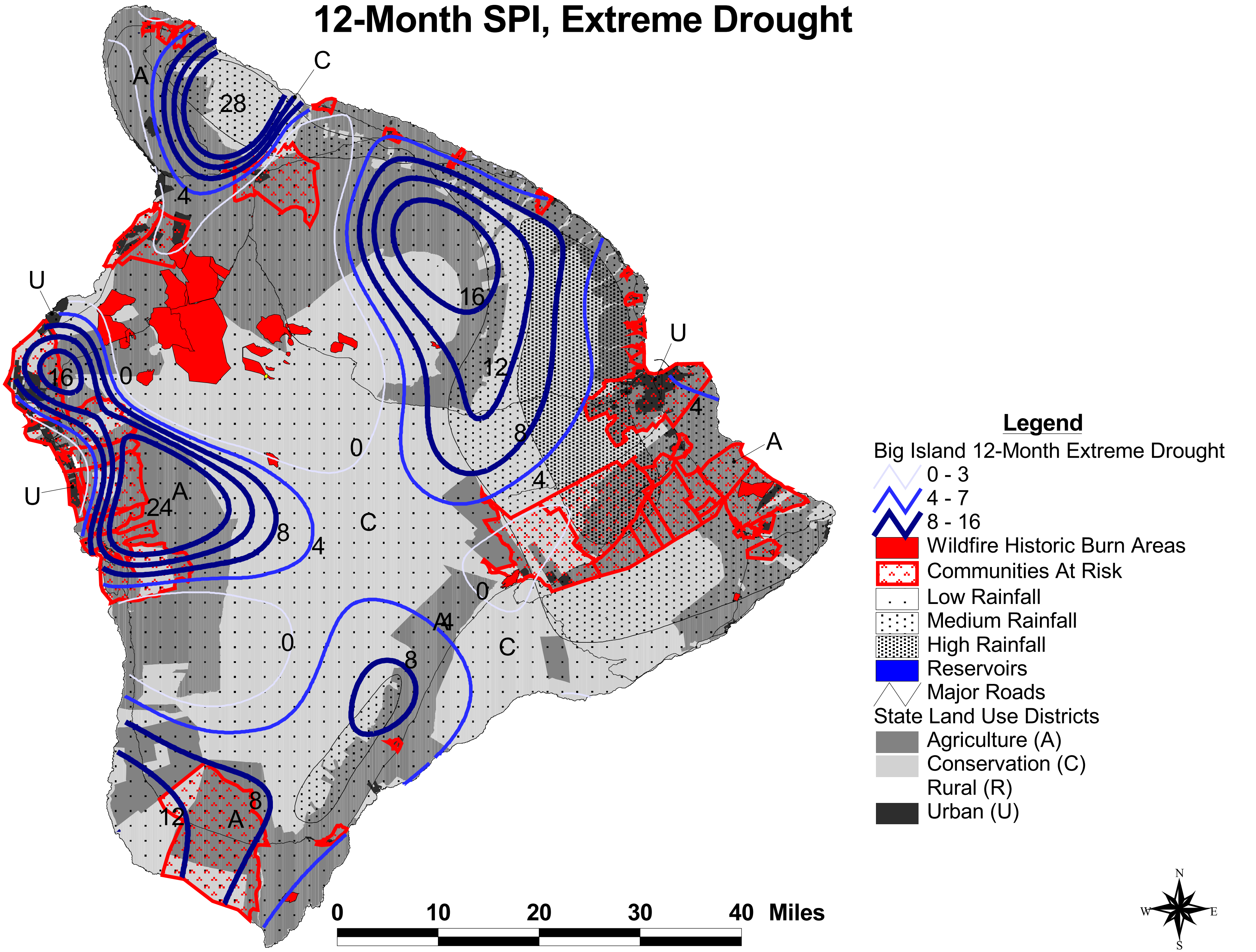


Figure 5.13. Drought Risk Areas
Water Supply Sector, County of Maui
12-Month SPI, Moderate Drought

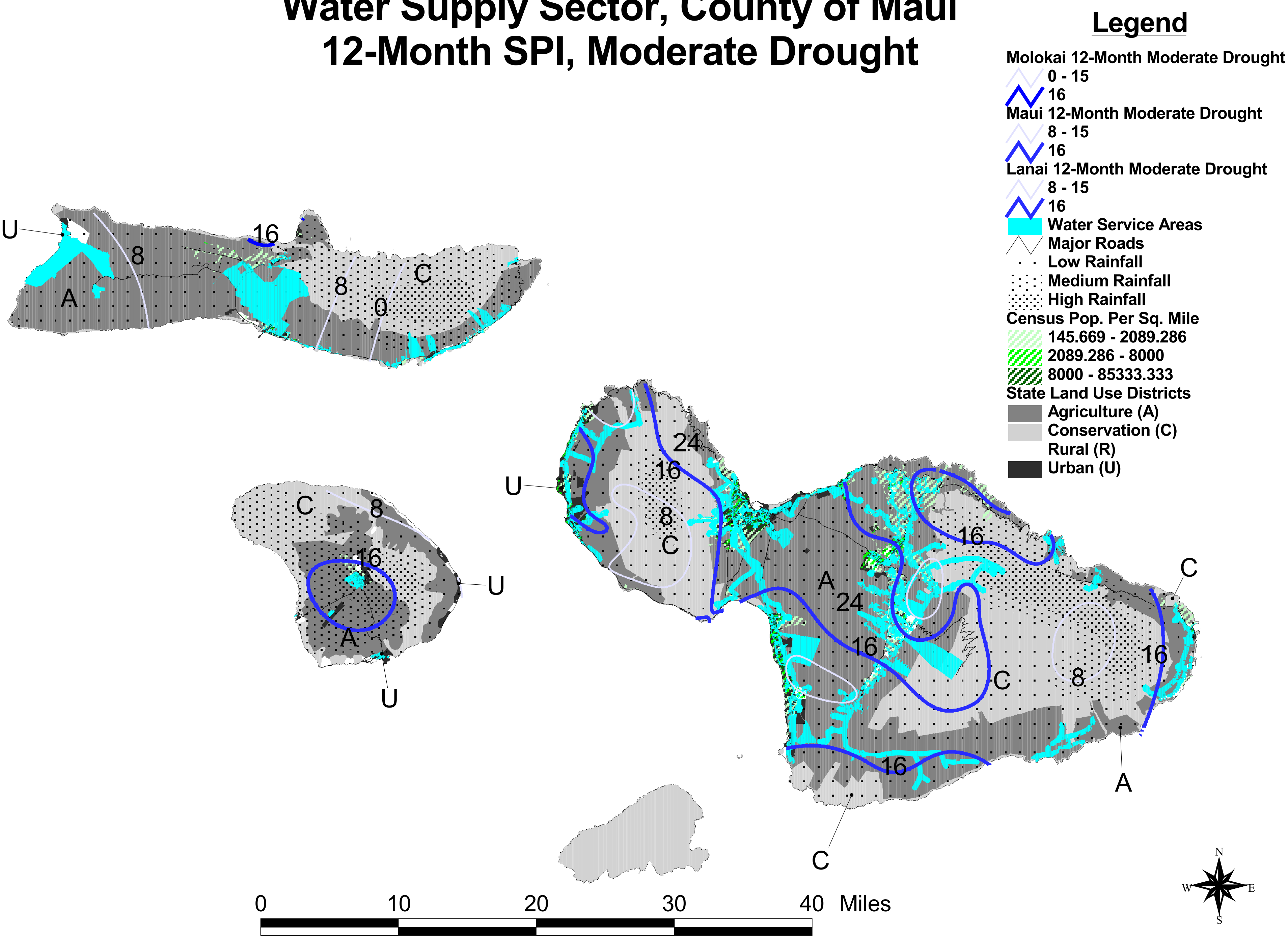


Figure 5.14. Drought Risk Areas
Water Supply Sector, County of Maui
12-Month SPI, Severe Drought

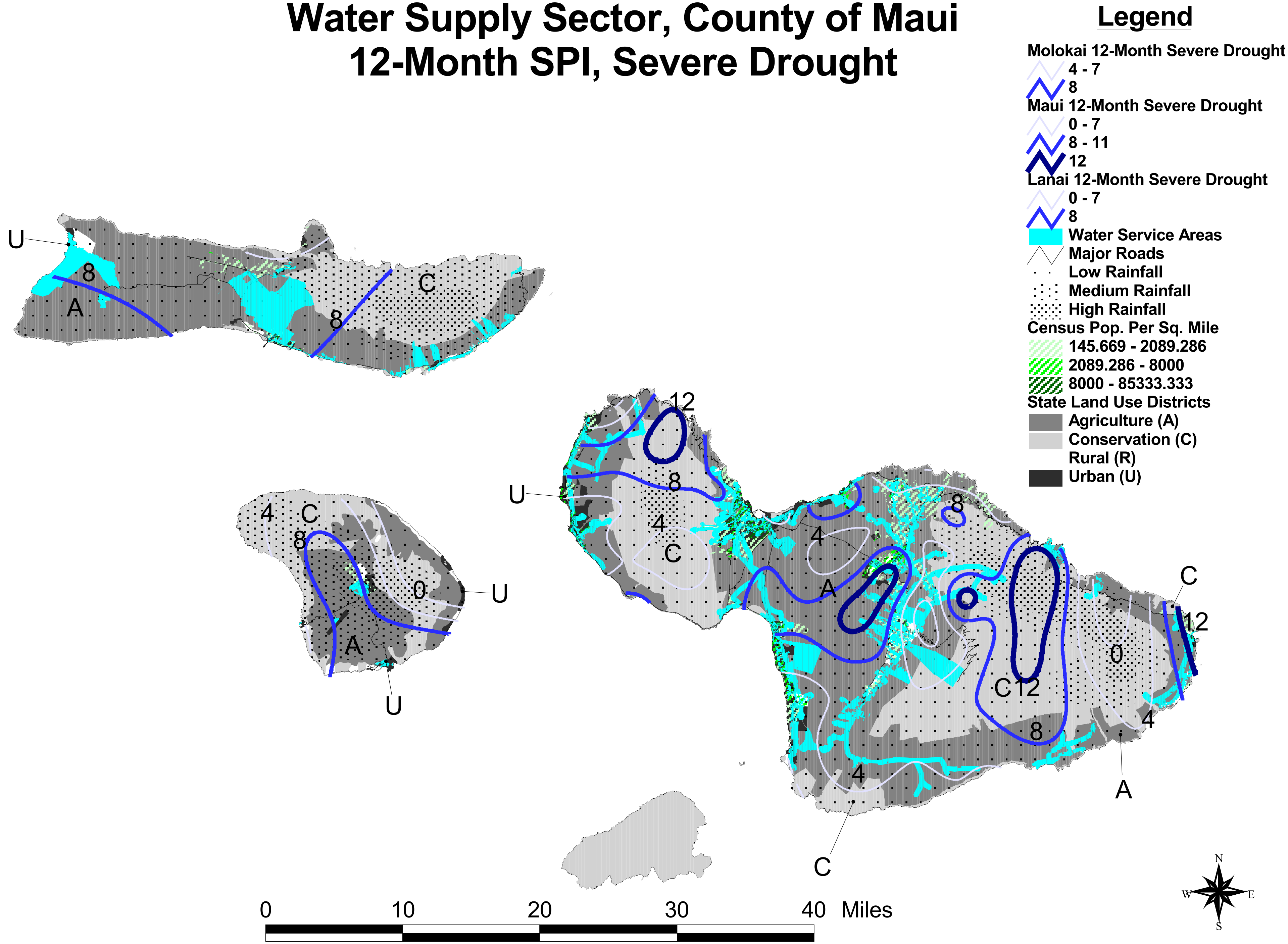


Figure 5.15. Drought Risk Areas Water Supply Sector, County of Maui 12-Month SPI, Extreme Drought

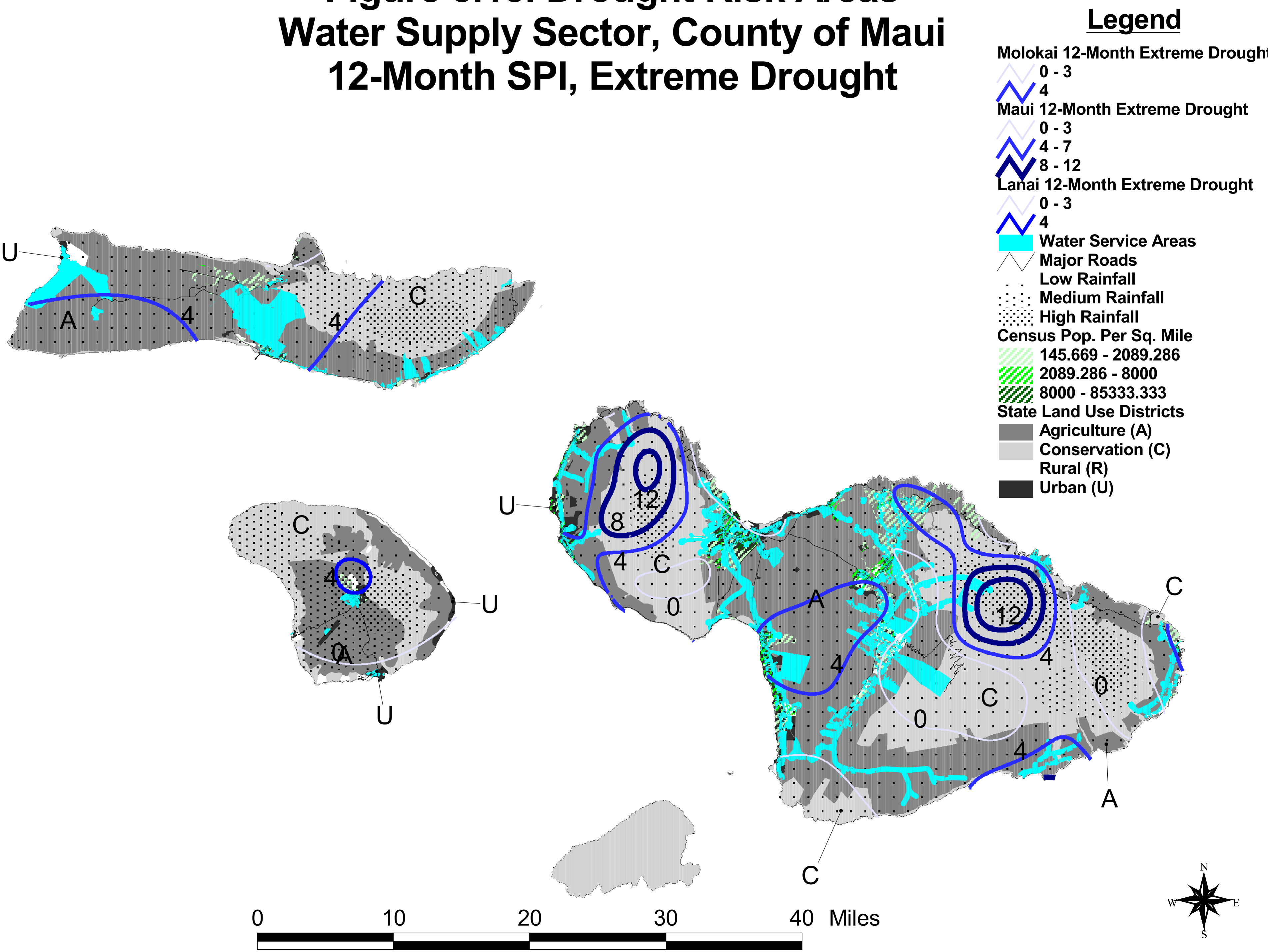


Figure 5.16. Drought Risk Areas Agriculture Sector, County of Maui 3-Month SPI, Moderate Drought

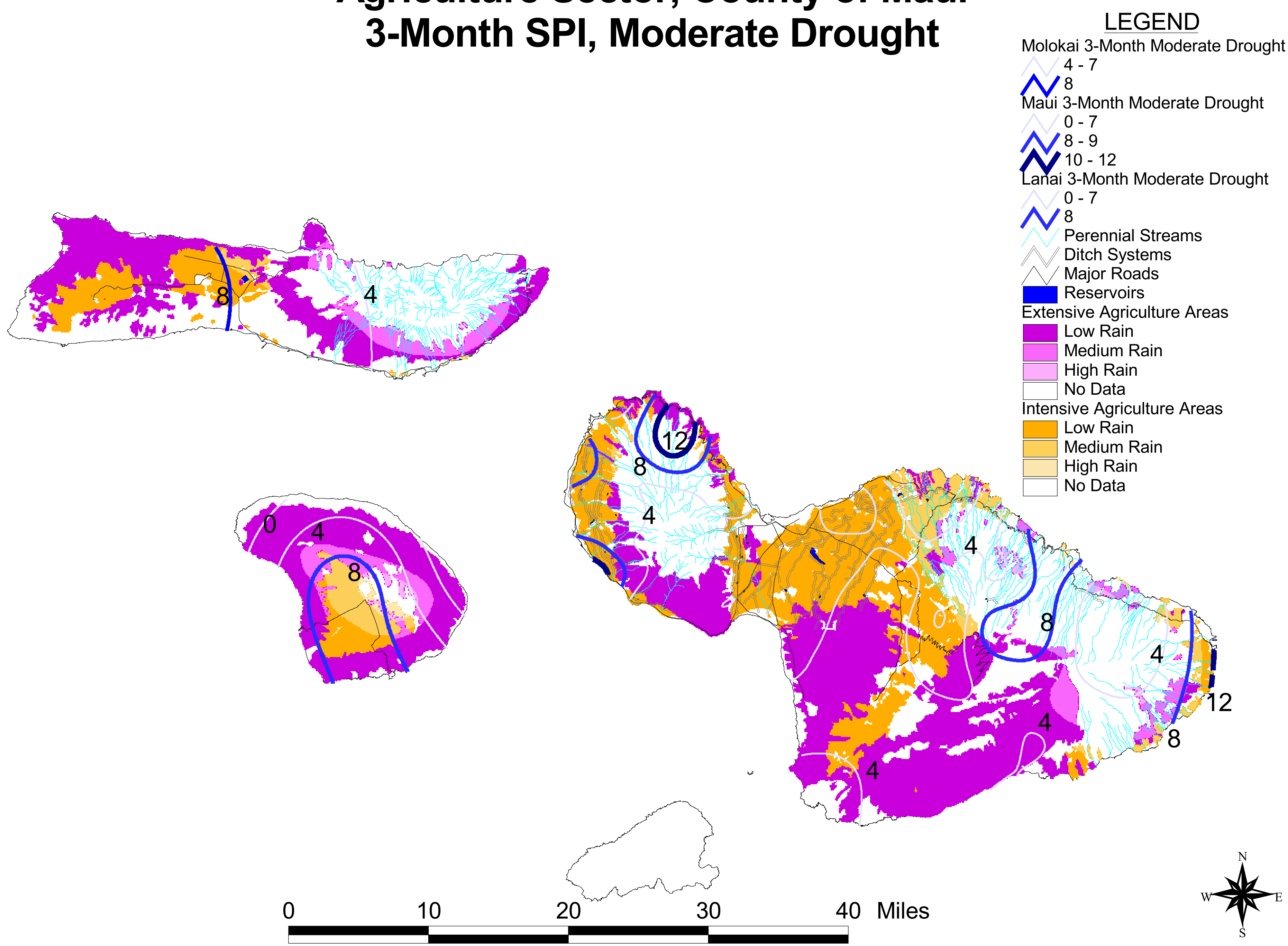


Figure 5.17. Drought Risk Areas Agriculture Sector, County of Maui 3-Month SPI, Severe Drought

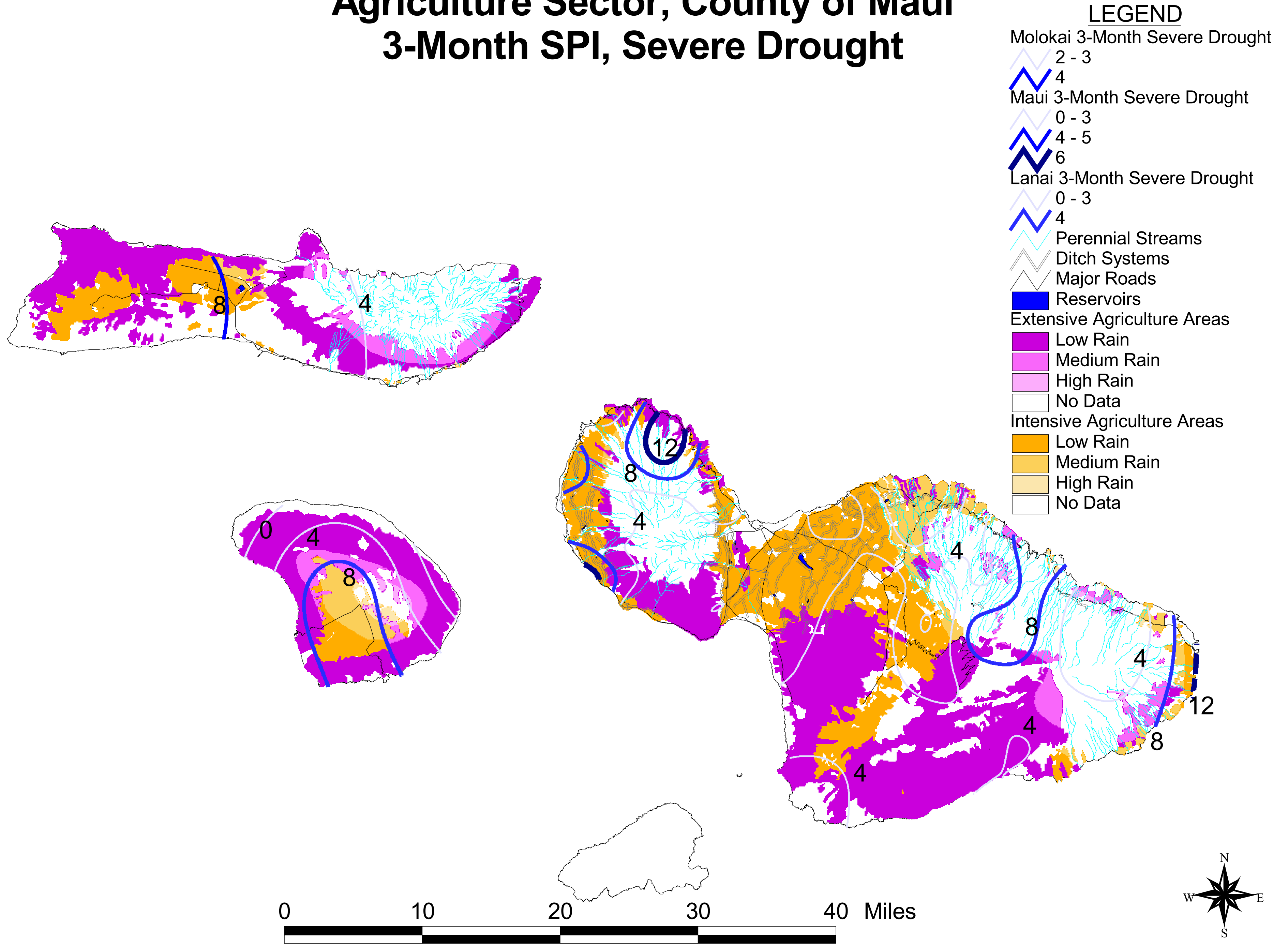


Figure 5.18. Drought Risk Areas Agriculture Sector, County of Maui 3-Month SPI, Extreme Drought

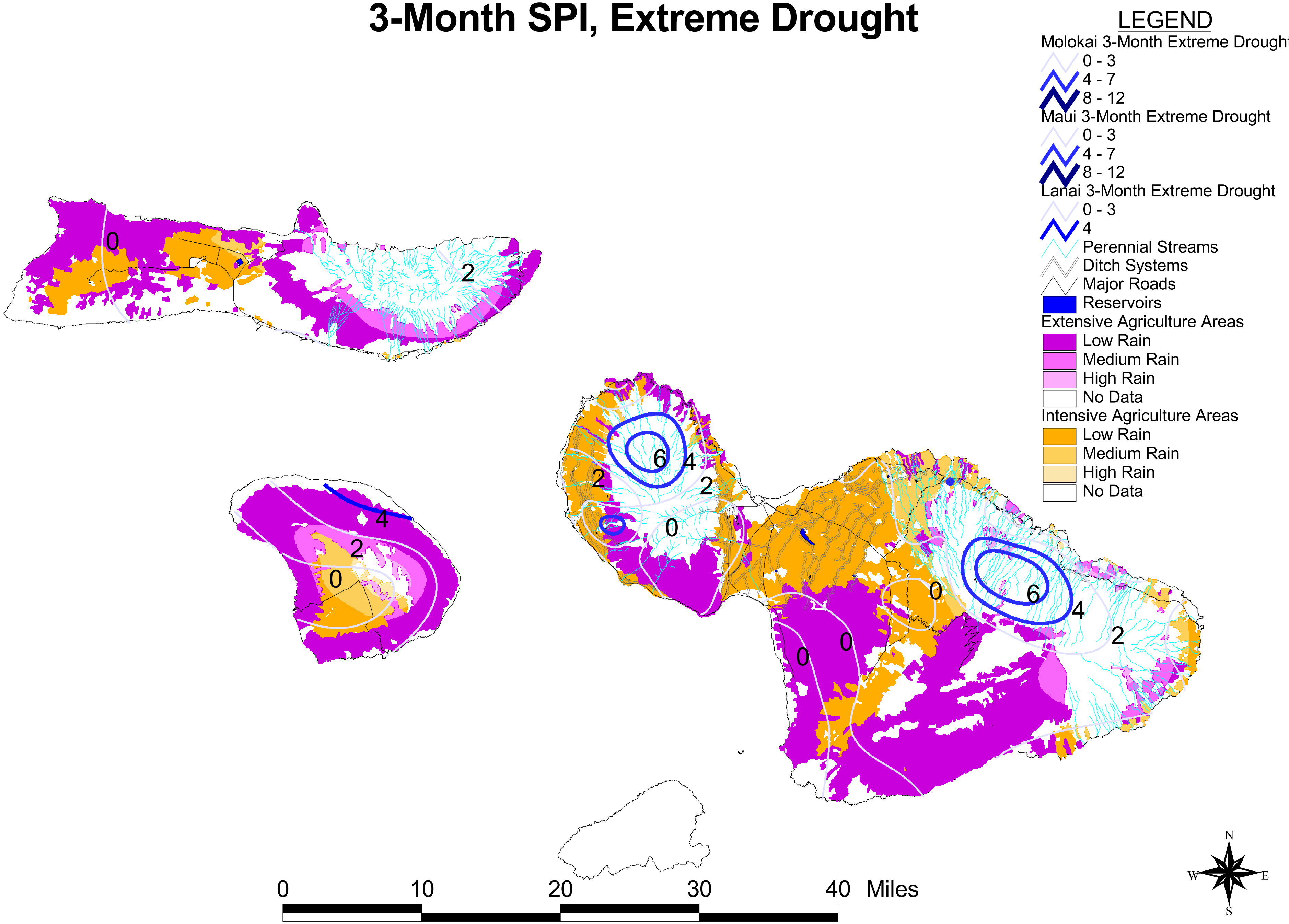


Figure 5.19. Drought Risk Areas
Environment, Public Health, and Safety Sector, County of Maui
3-Month SPI, Moderate Drought

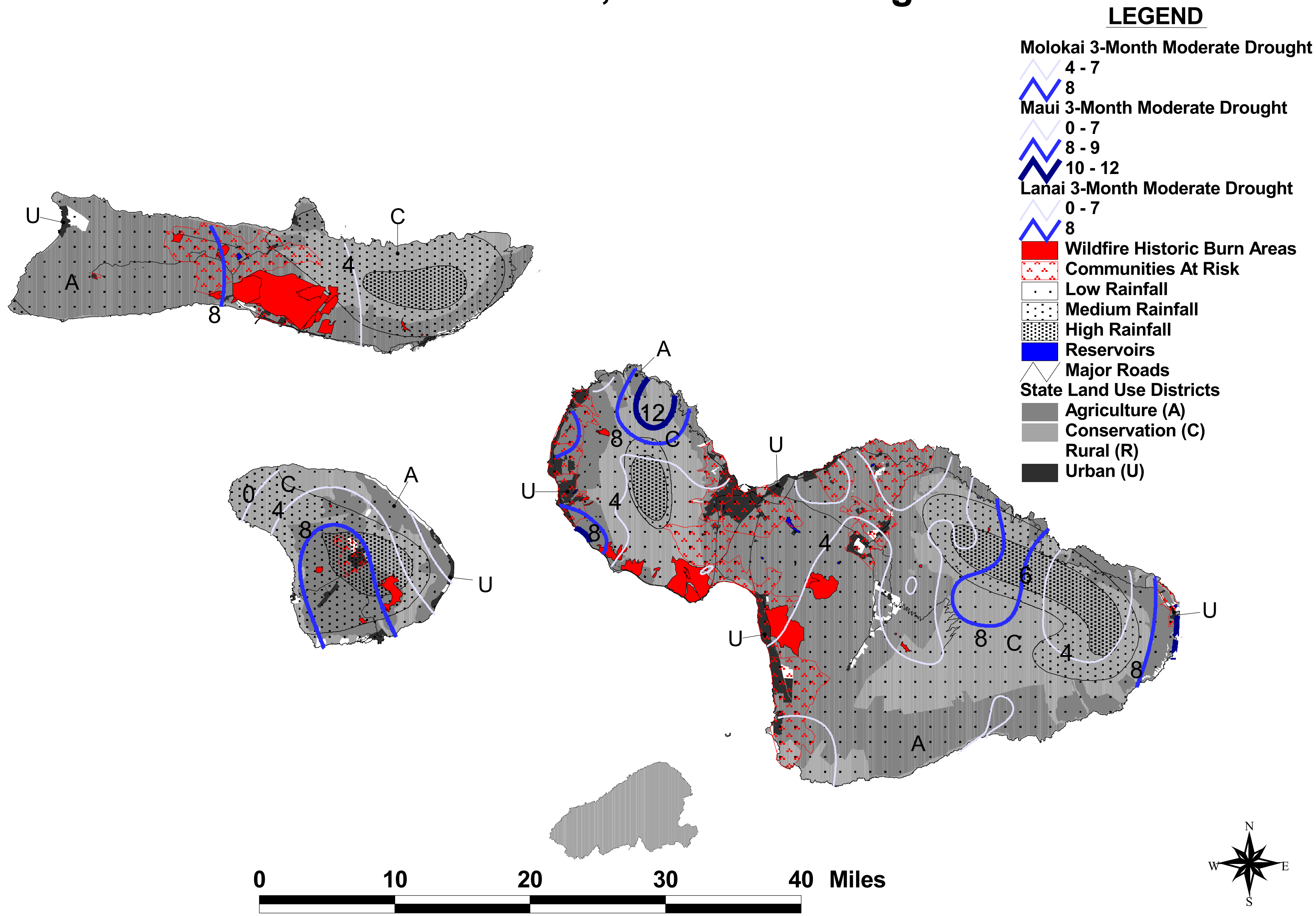


Figure 5.20. Drought Risk Areas
Environment, Public Health, and Safety Sector, County of Maui
3-Month SPI, Severe Drought

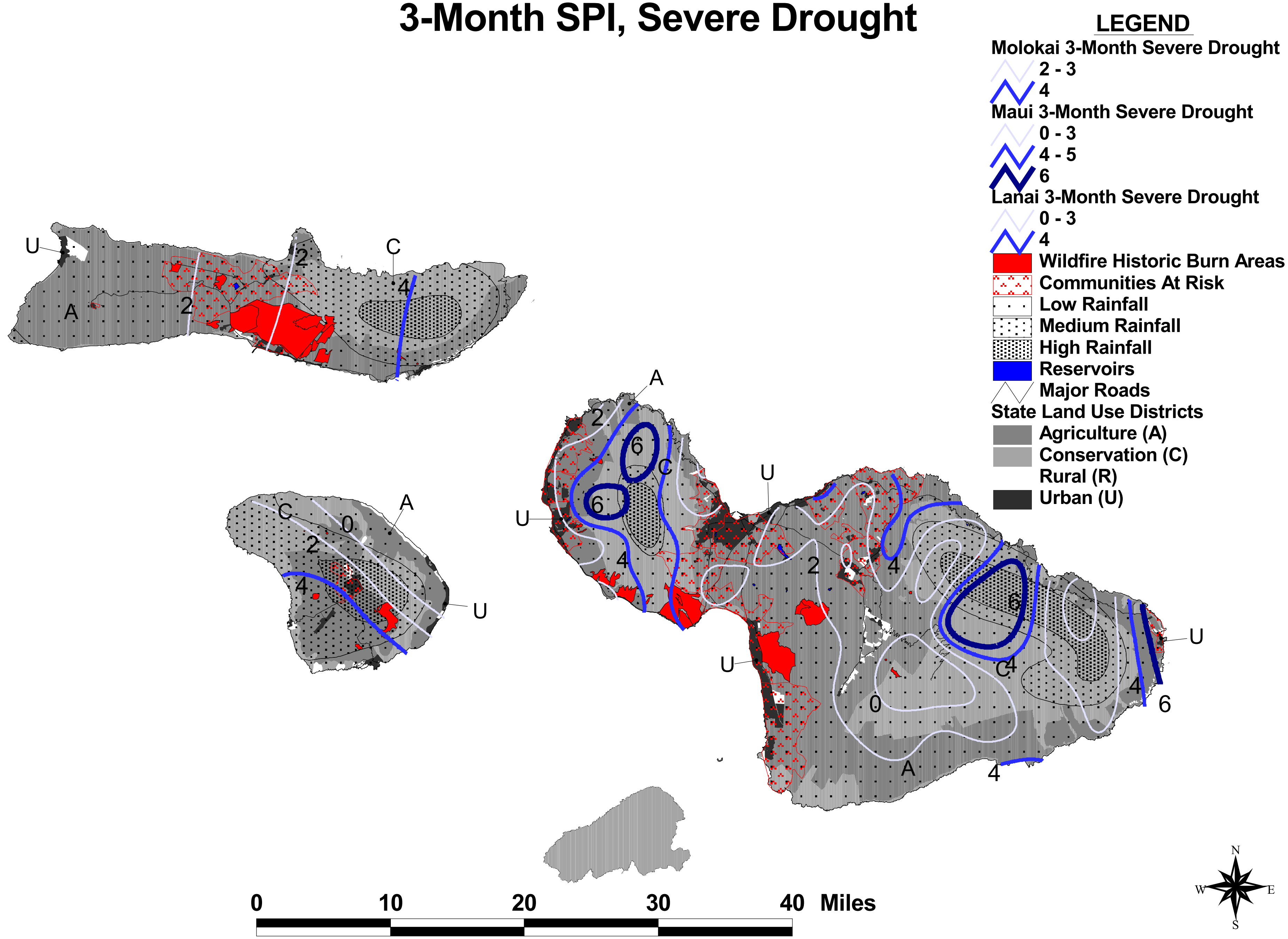


Figure 5.21. Drought Risk Areas
Environment, Public Health, and Safety Sector, County of Maui
3-Month SPI, Extreme Drought

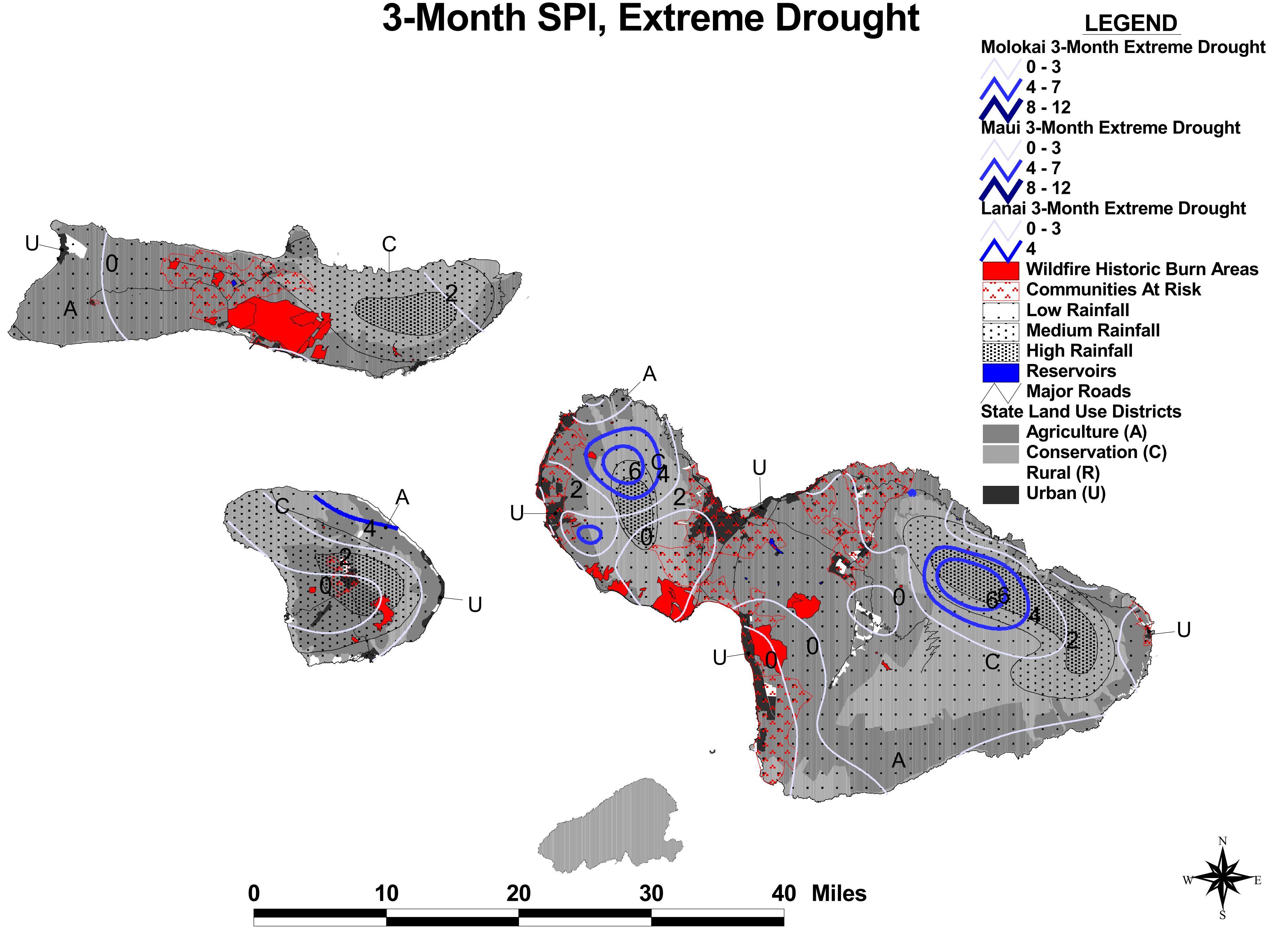


Figure 5.22. Drought Risk Areas
Environment, Public Health, and Safety Sector, County of Maui
12-Month SPI, Moderate Drought

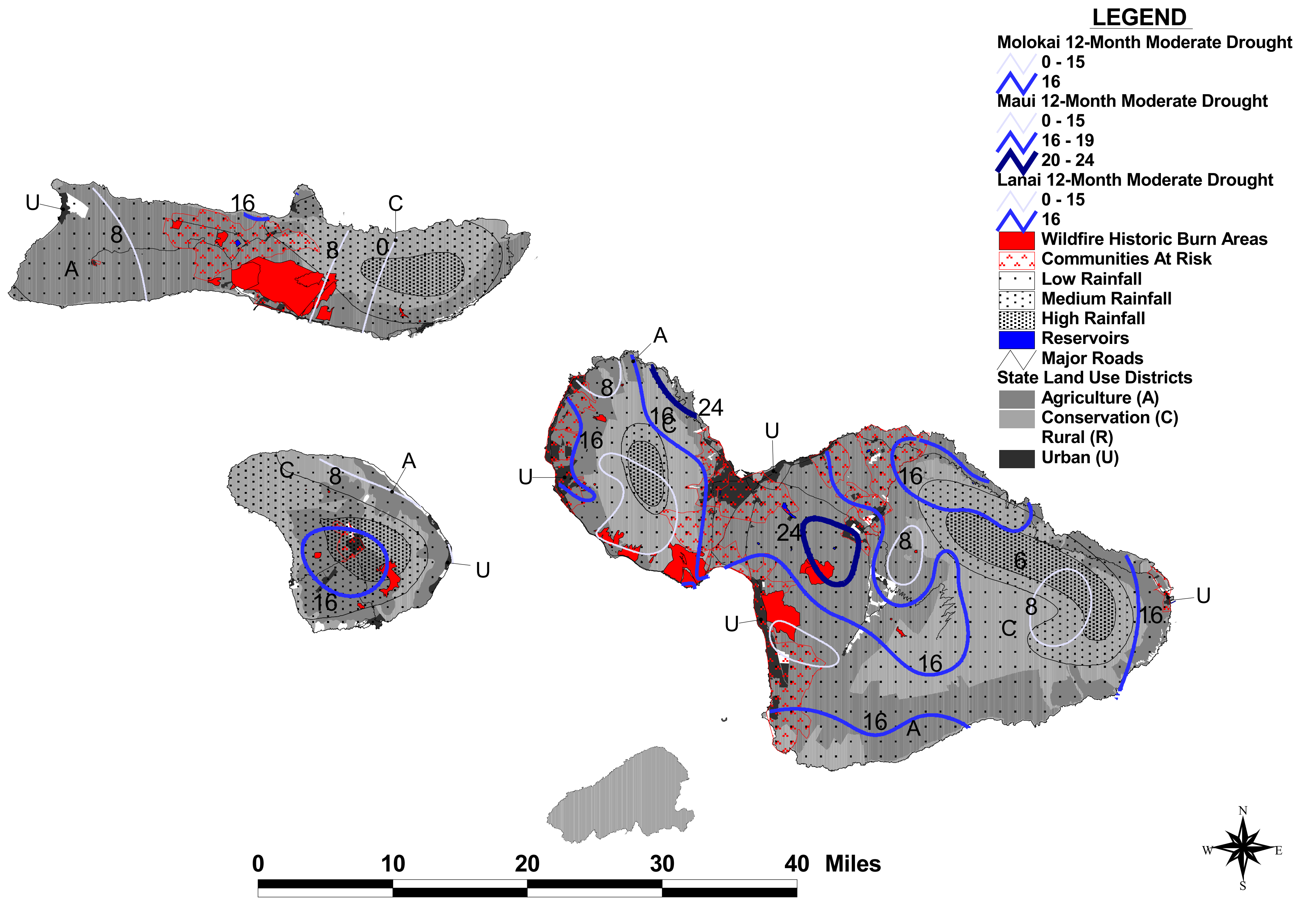


Figure 5.23. Drought Risk Areas
Environment, Public Health, and Safety Sector, County of Maui
12-Month SPI, Severe Drought

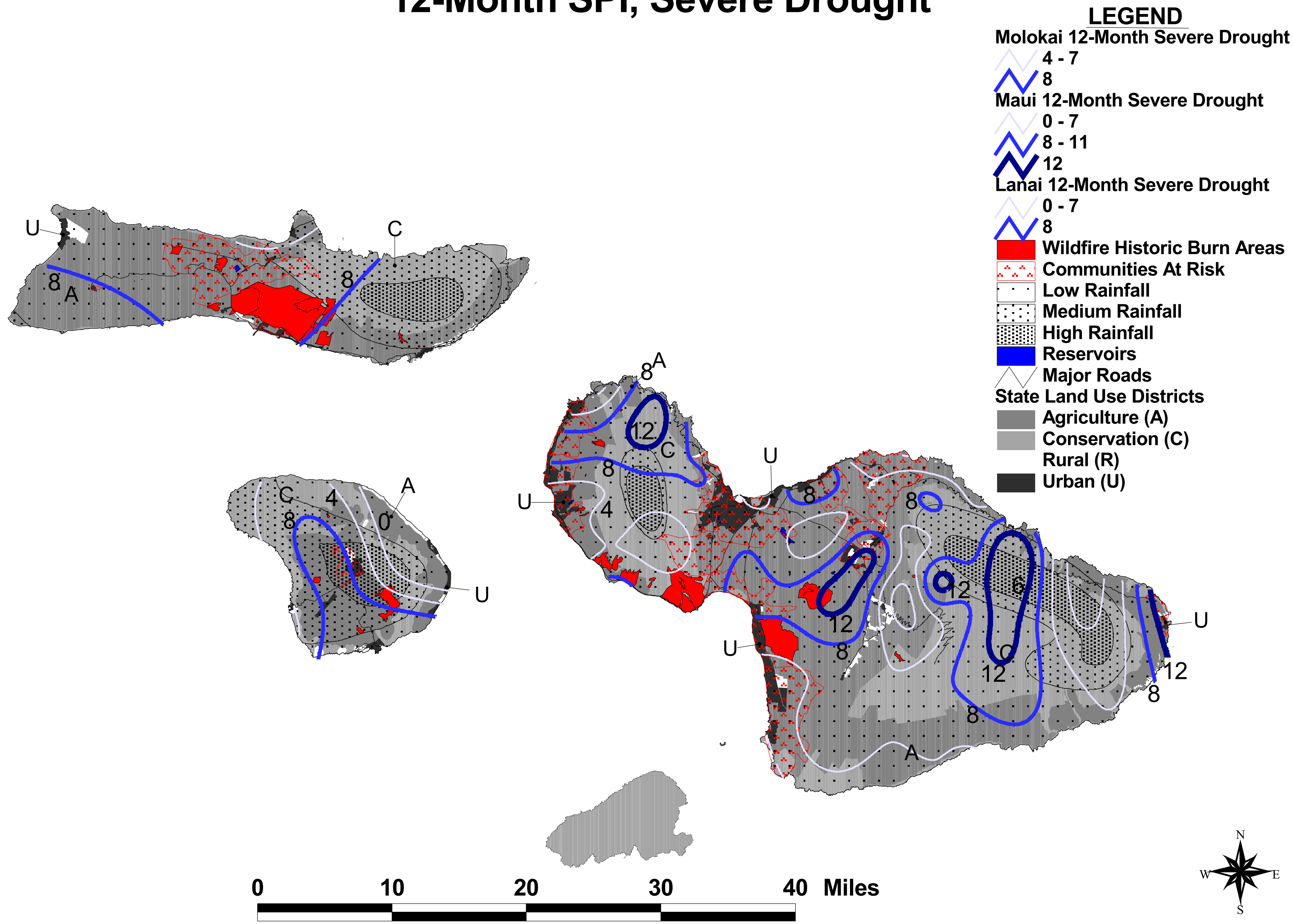


Figure 5.24. Drought Risk Areas
Environment, Public Health, and Safety Sector, County of Maui
12-Month SPI, Extreme Drought

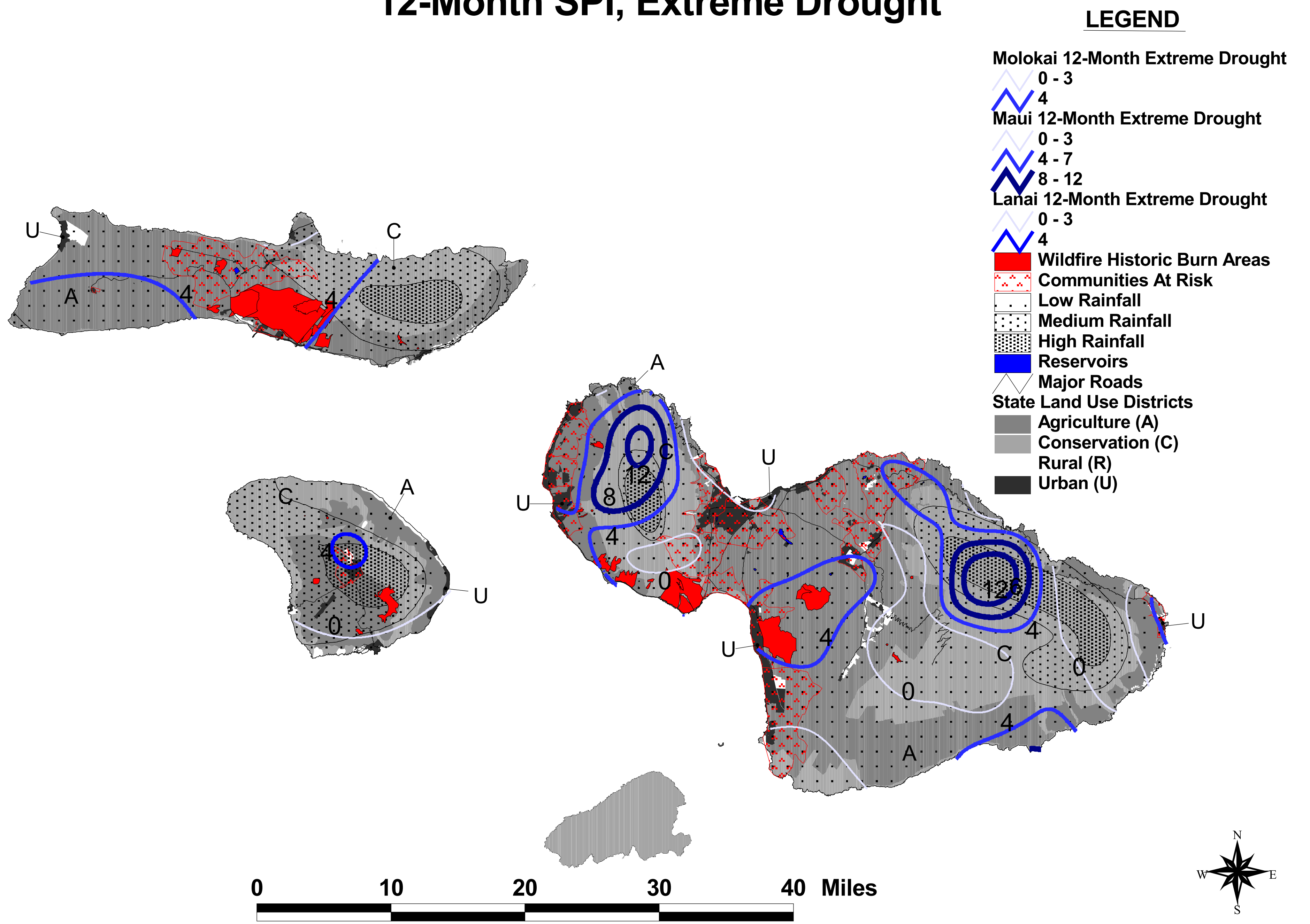


Figure 5.25. Drought Risk Areas
Water Supply Sector, City and County of Honolulu
12-Month SPI, Moderate Drought

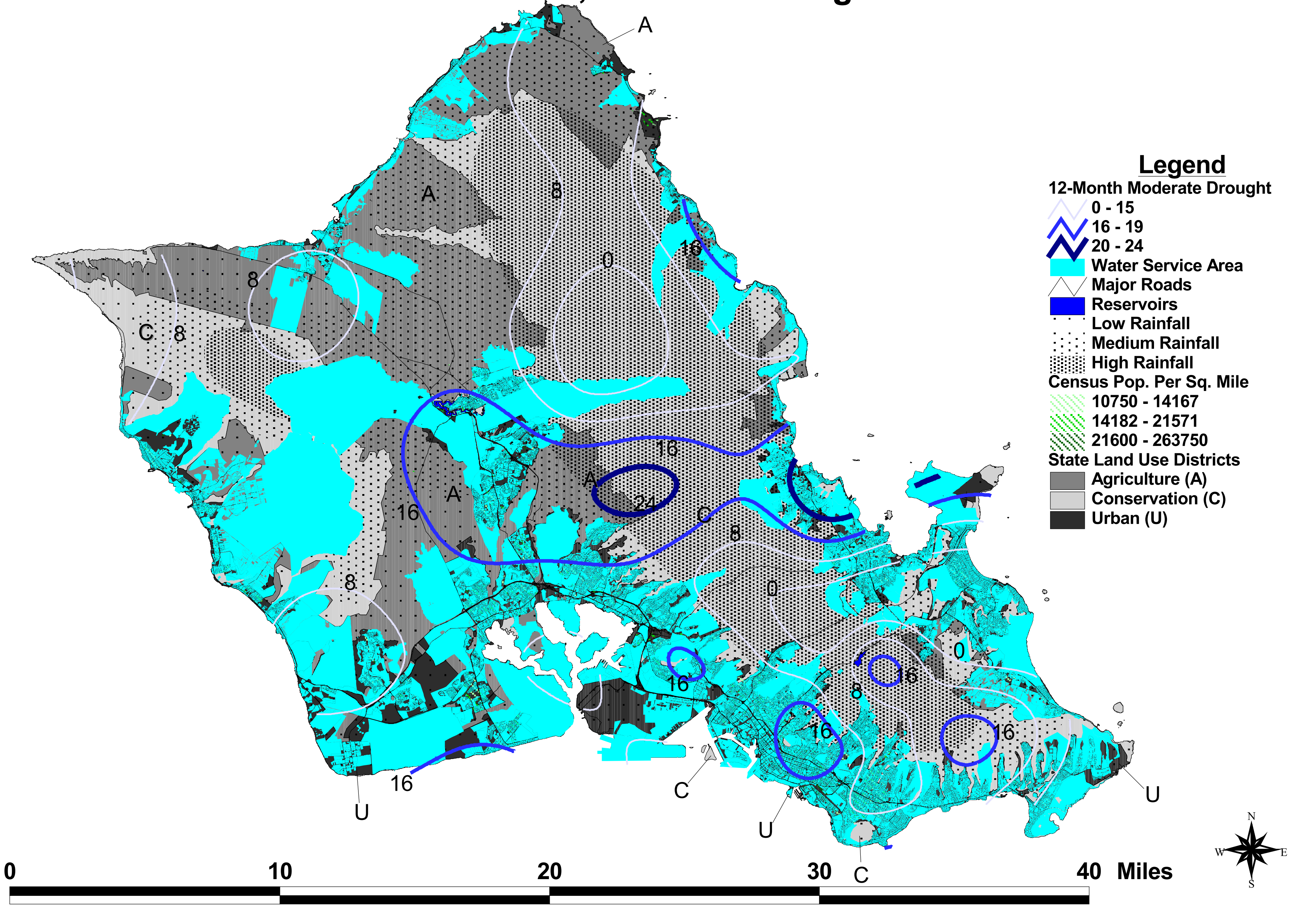


Figure 5.26. Drought Risk Areas
Water Supply Sector, City and County of Honolulu
12-Month SPI, Severe Drought

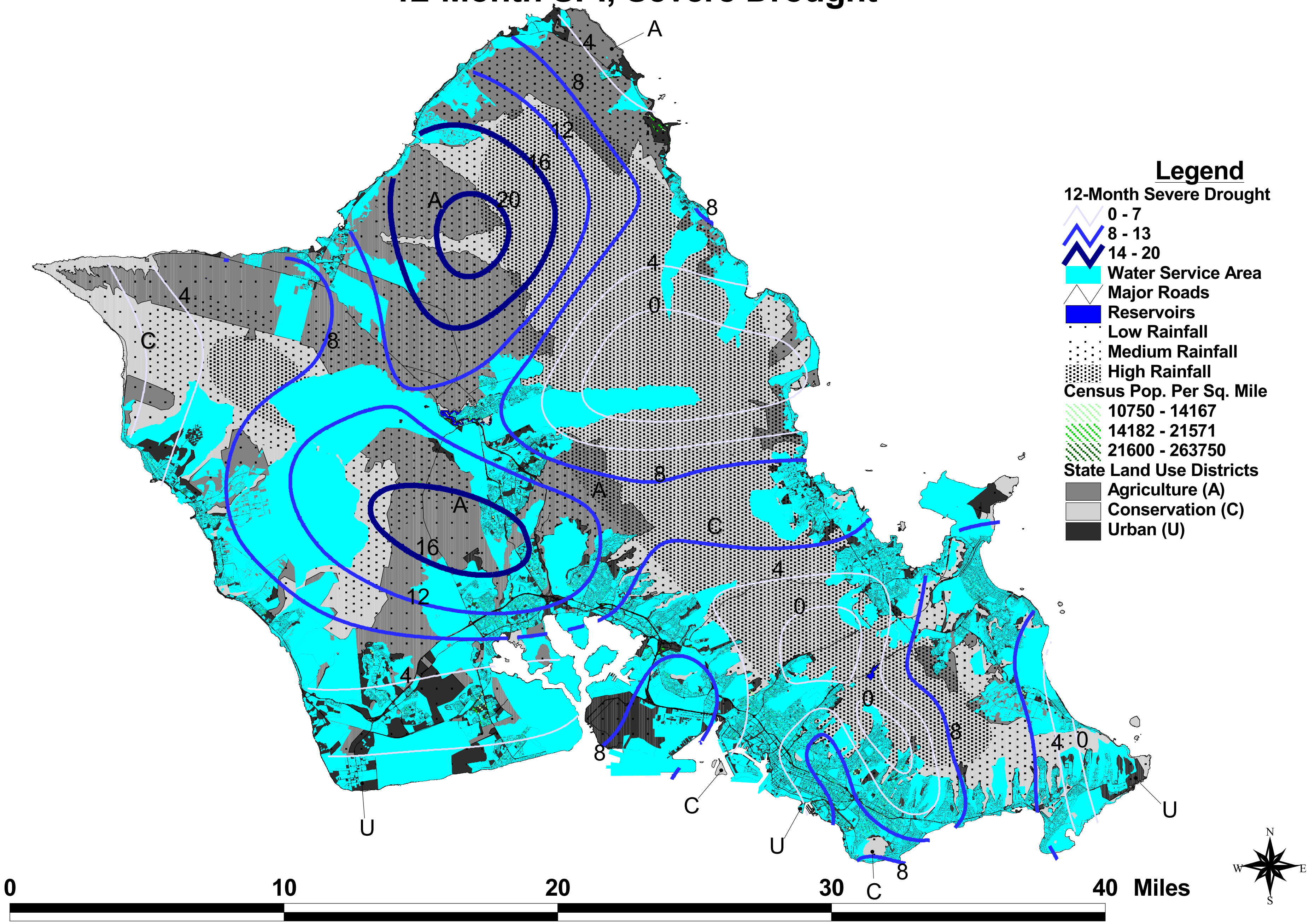


Figure 5.27. Drought Risk Areas
Water Supply Sector, City and County of Honolulu
12-Month SPI, Extreme Drought

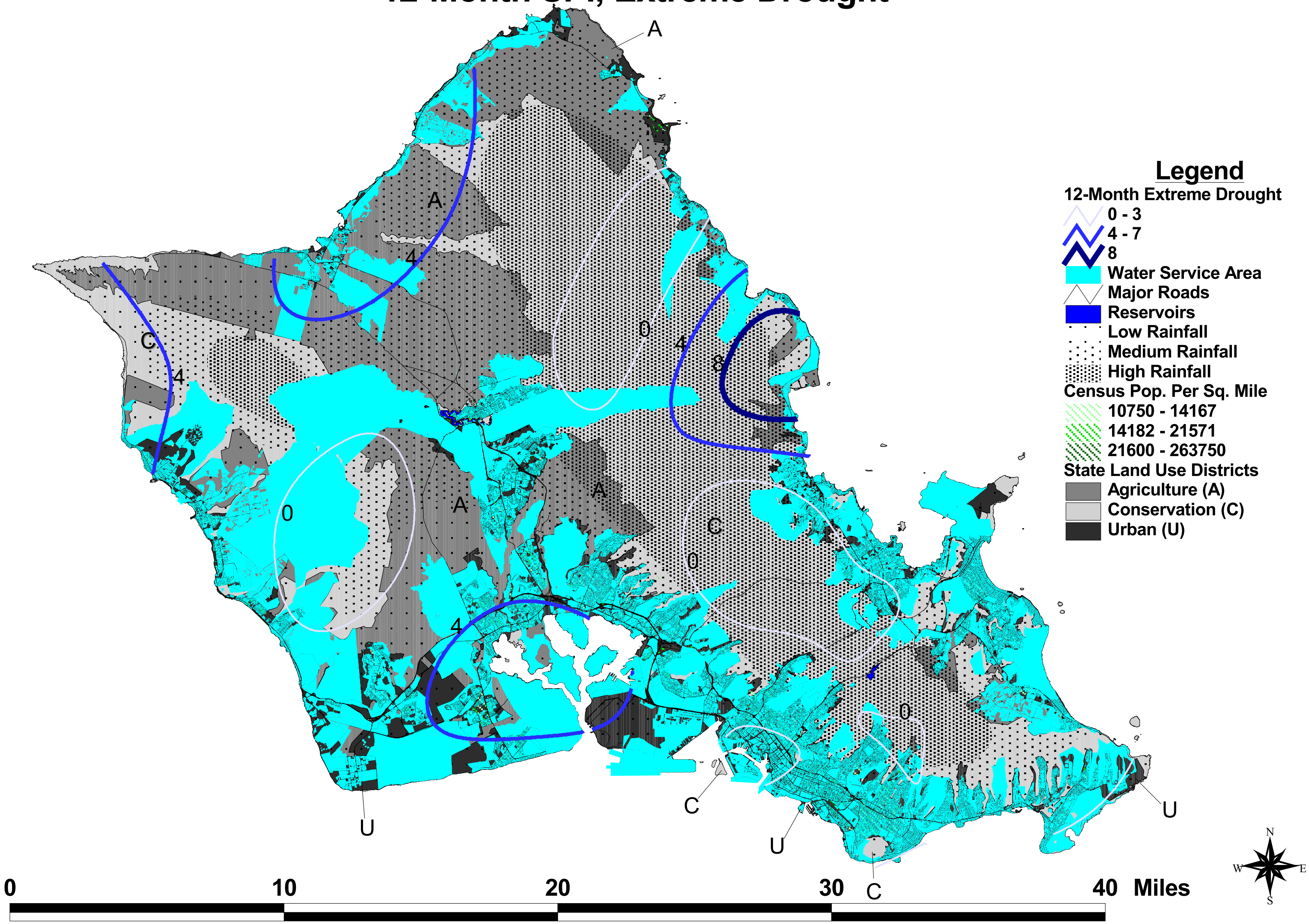


Figure 5.28. Drought Risk Areas
Agriculture Sector, City and County of Honolulu
3-Month SPI, Moderate Drought

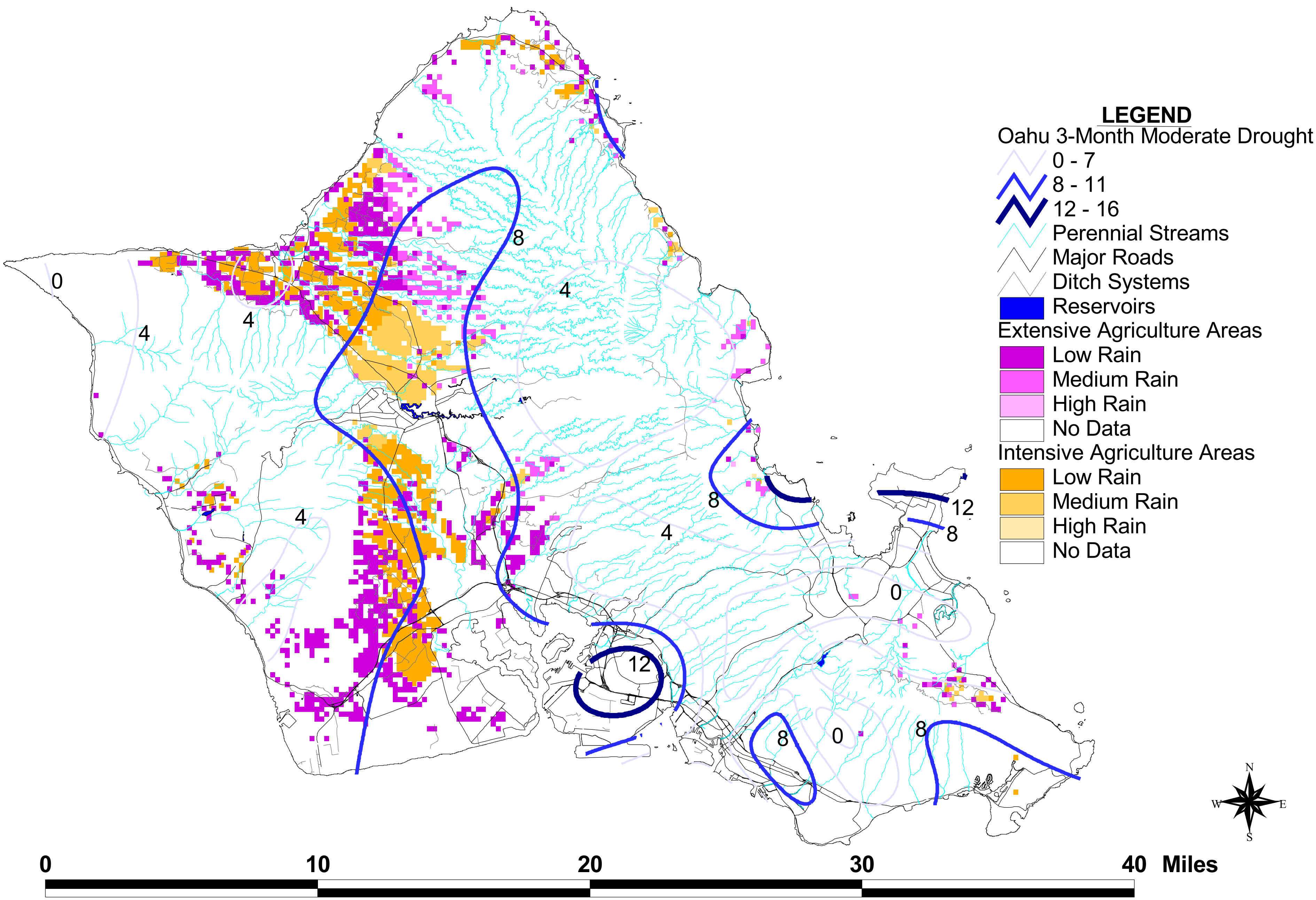


Figure 5.29. Drought Risk Areas
Agriculture Sector, City and County of Honolulu
3-Month SPI, Severe Drought

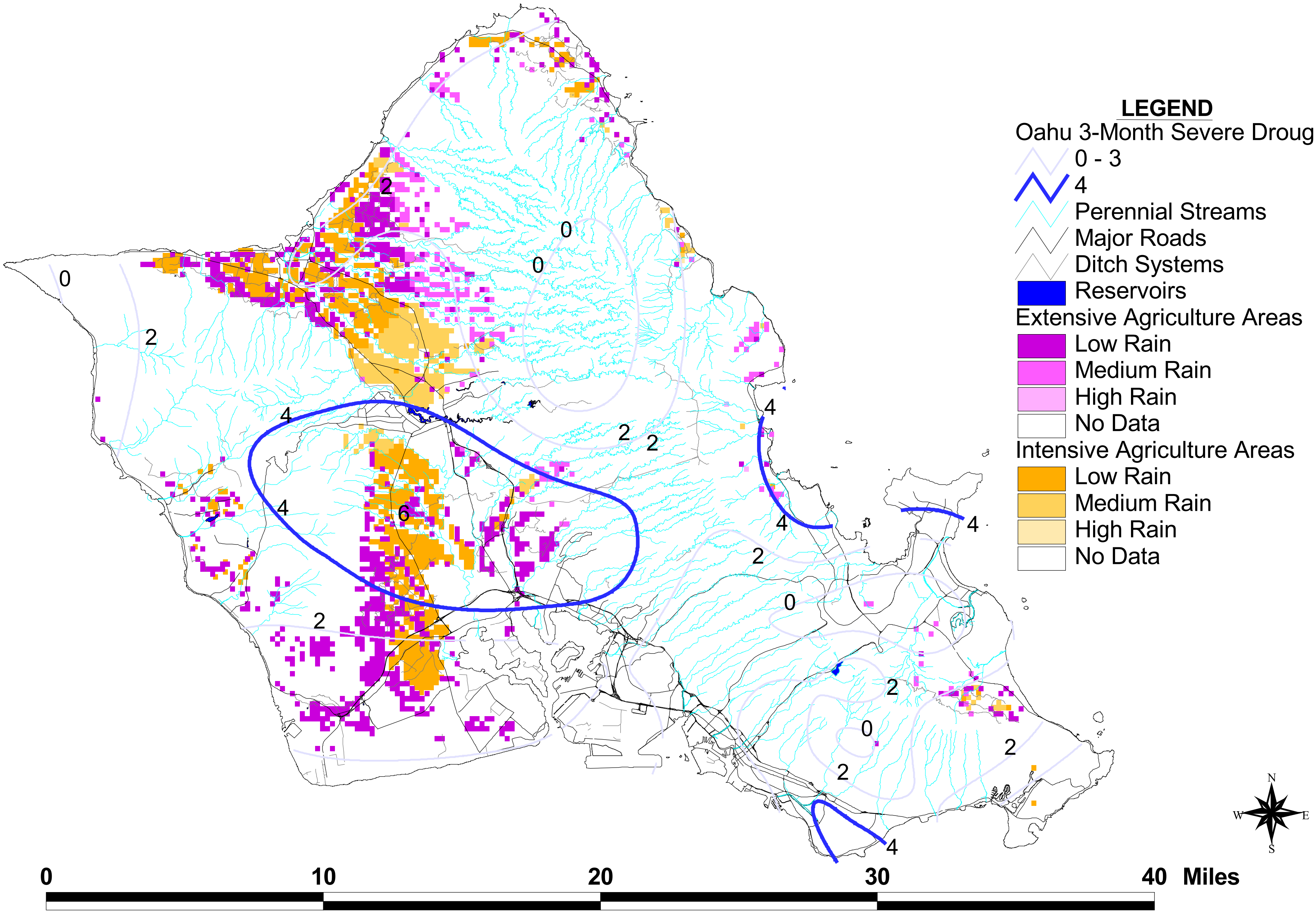


Figure 5.30. Drought Risk Areas
Agriculture Sector, City and County of Honolulu
3-Month SPI, Extreme Drought

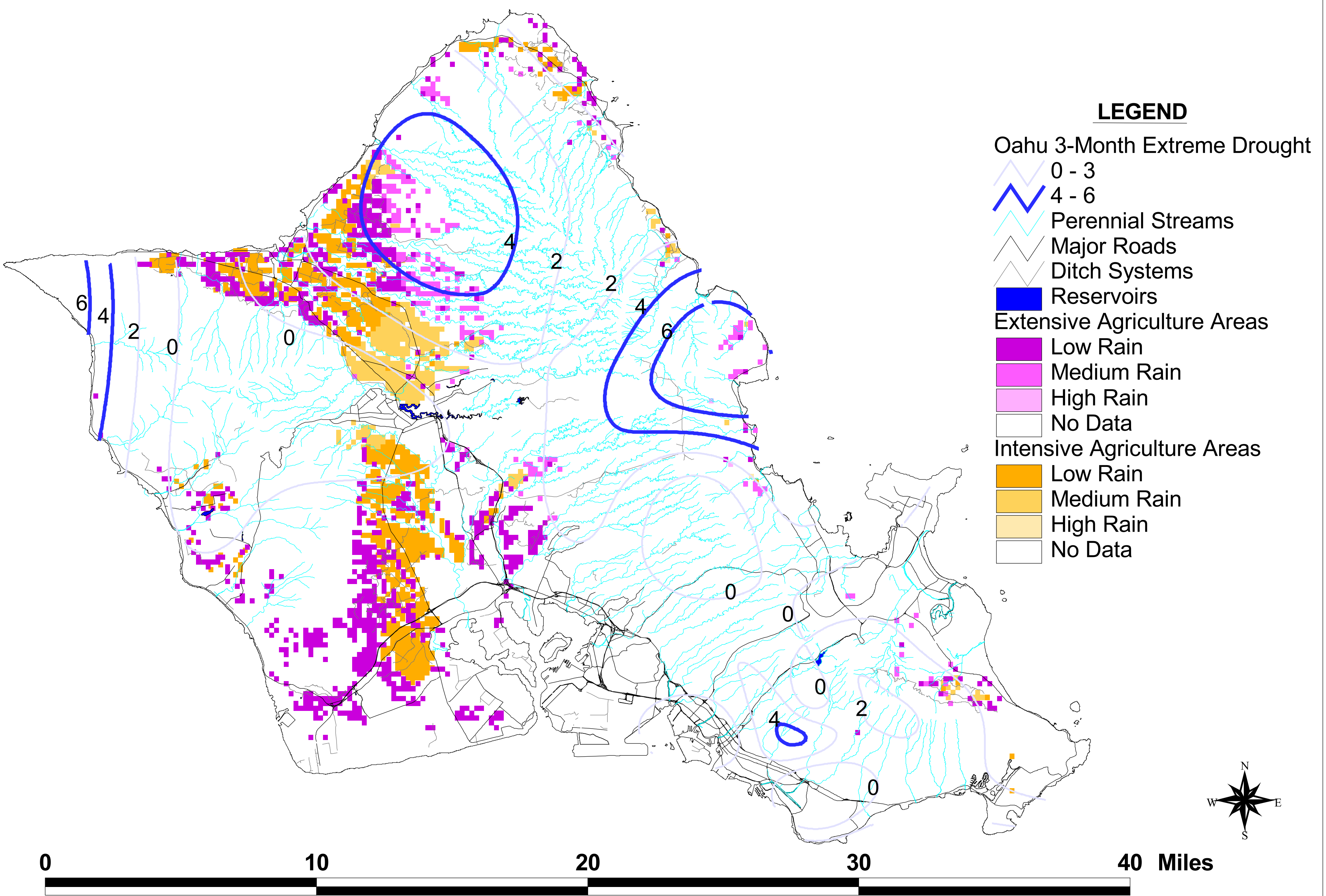


Figure 5.31. Drought Risk Areas
Environment, Public Health, and Safety Sector, City and County of Honolulu
3-Month SPI, Moderate Drought

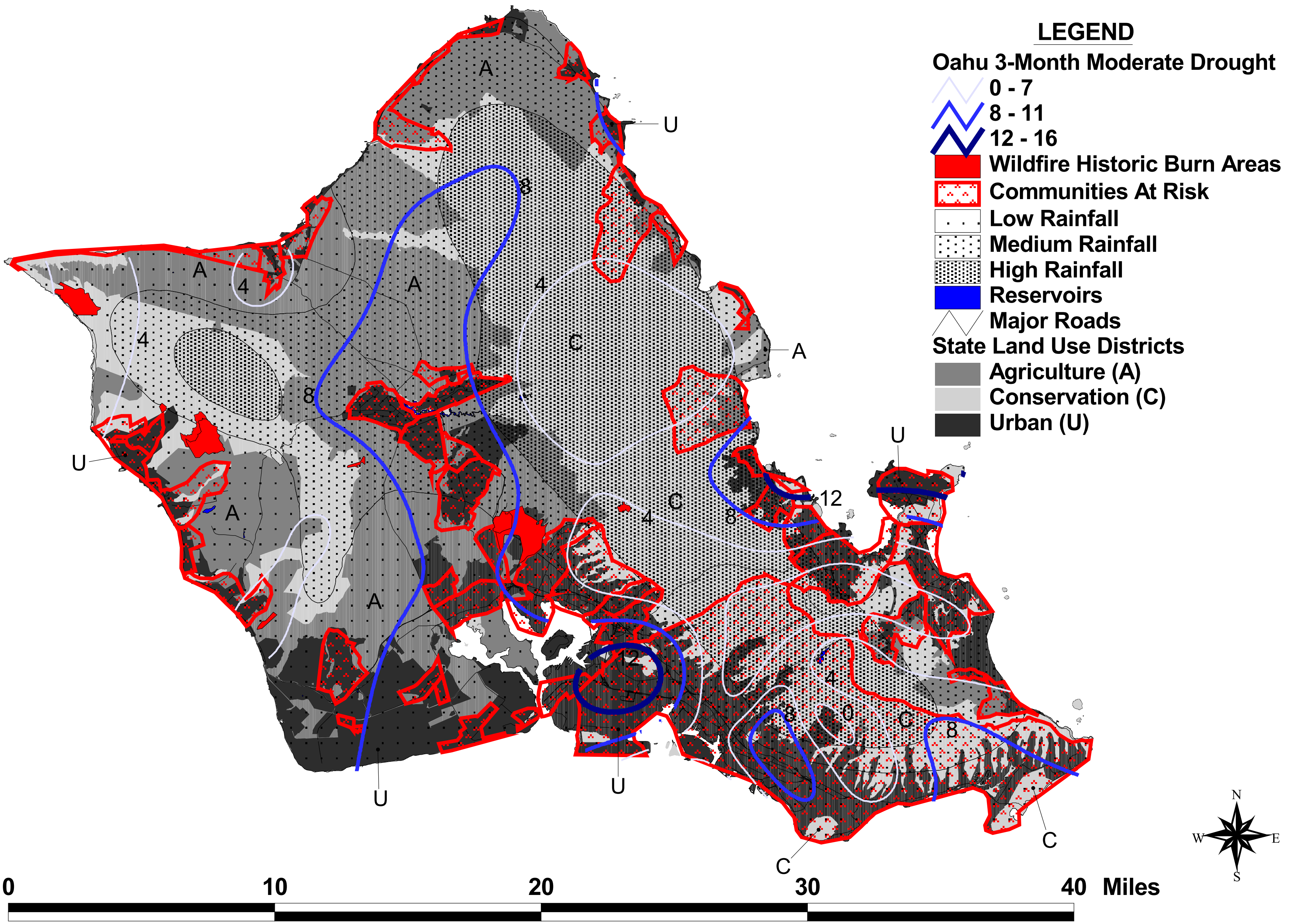


Figure 5.32. Drought Risk Areas
Environment, Public Health, and Safety Sector, City and County of Honolulu
3-Month SPI, Severe Drought

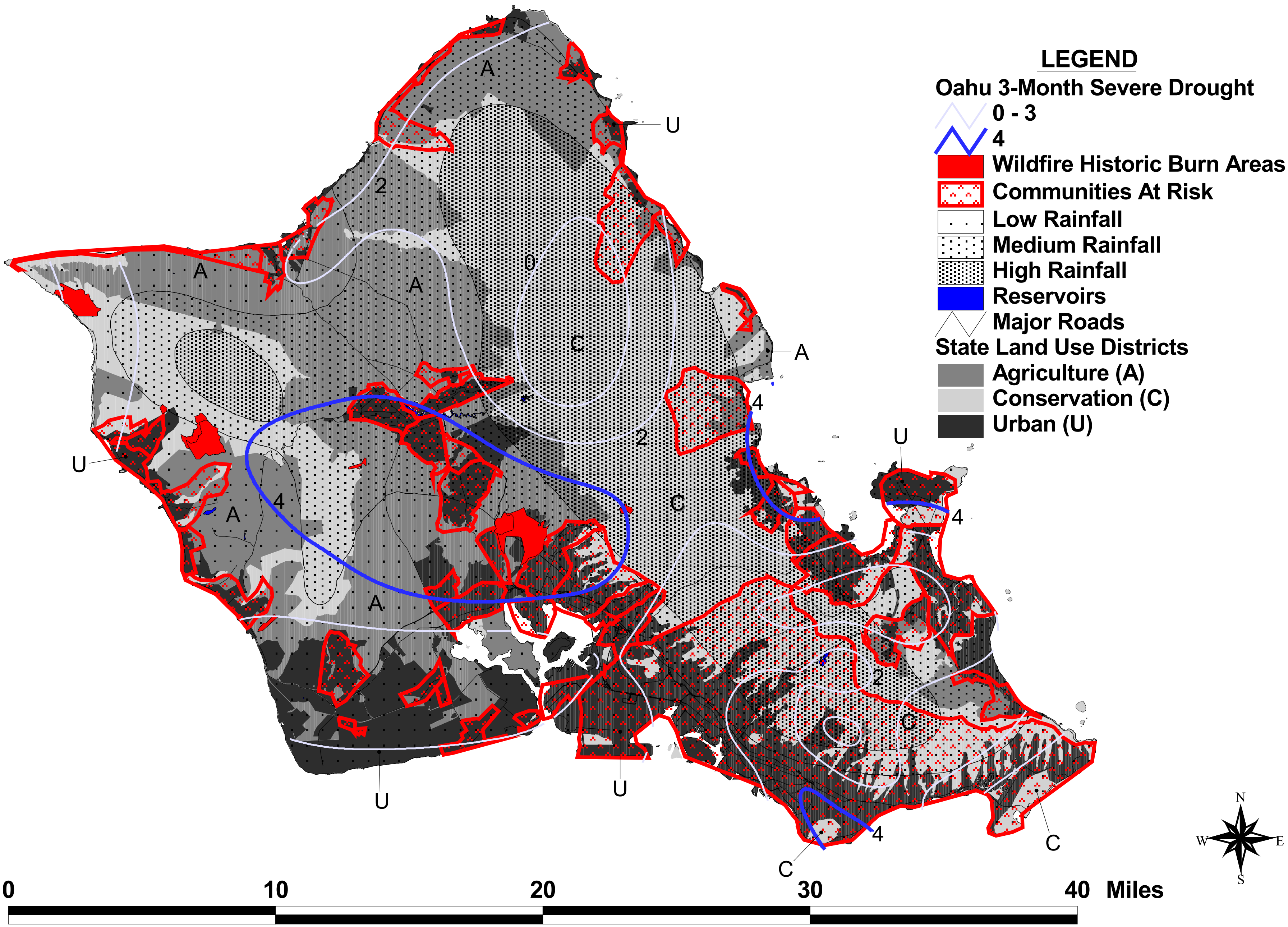


Figure 5.33. Drought Risk Areas
Environment, Public Health, and Safety Sector, City and County of Honolulu
3-Month SPI, Extreme Drought

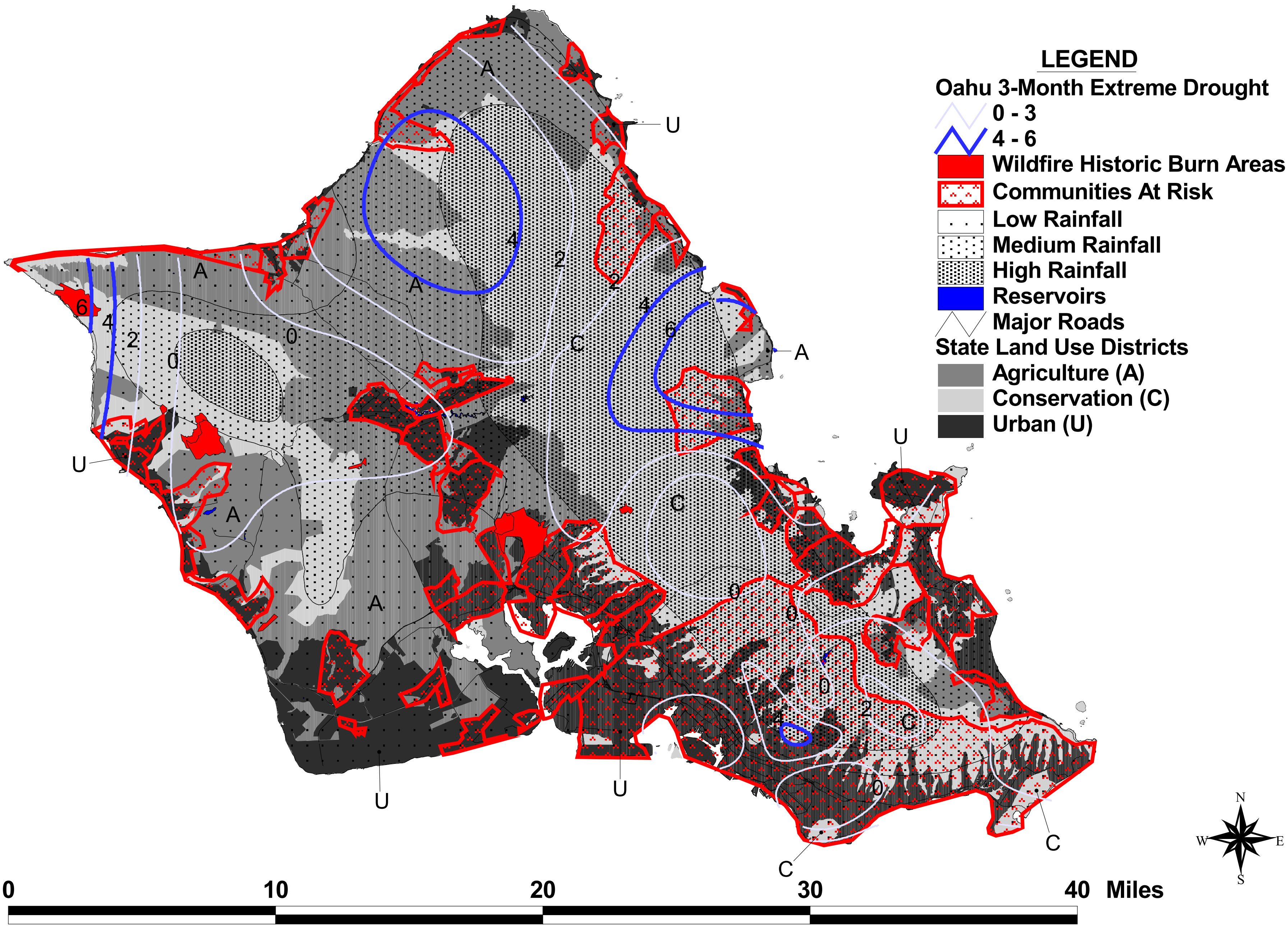


Figure 5.34. Drought Risk Areas
Environment, Public Health, and Safety Sector, City and County of Honolulu
12-Month SPI, Moderate Drought

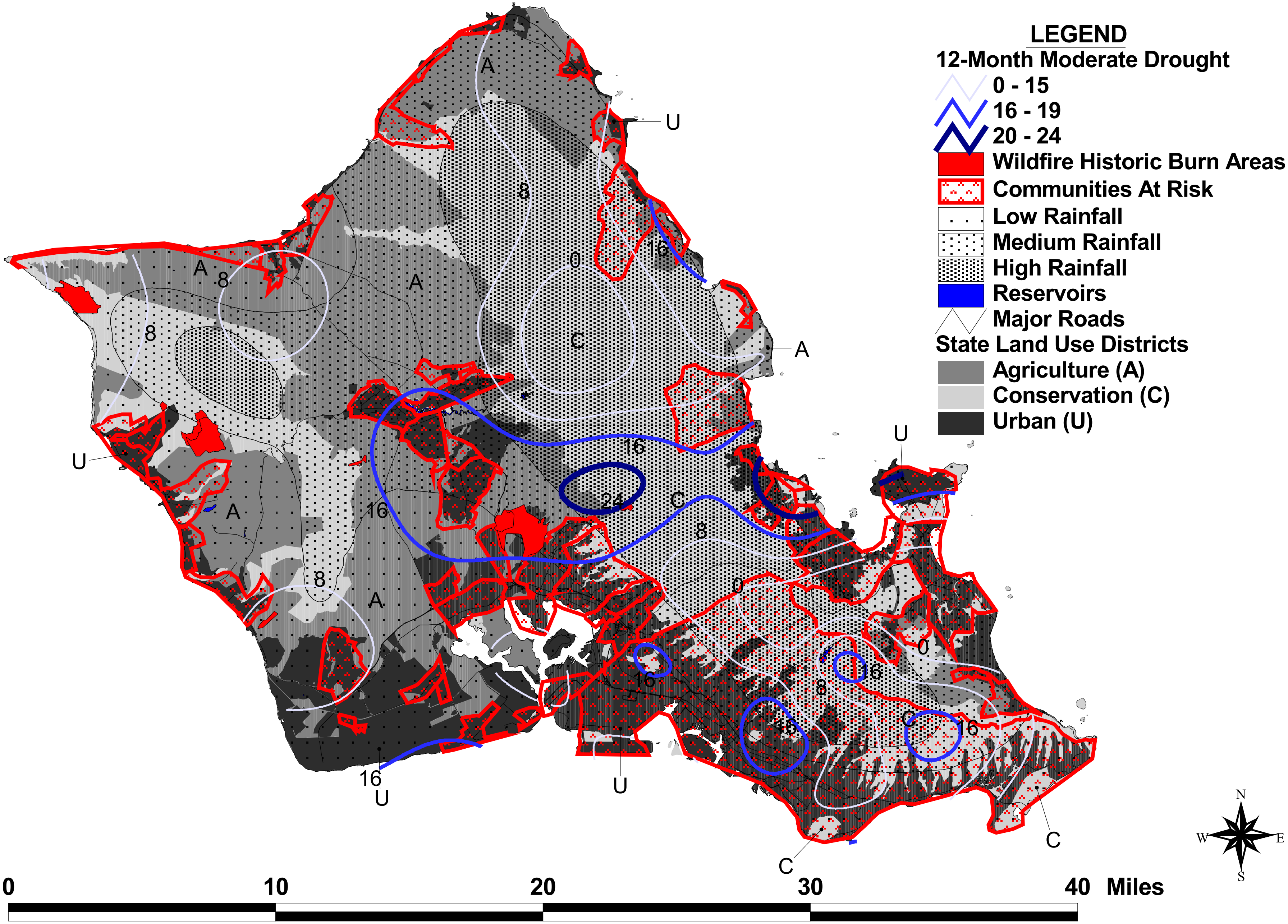


Figure 5.35. Drought Risk Areas
Environment, Public Health, and Safety Sector, City and County of Honolulu
12-Month SPI, Severe Drought

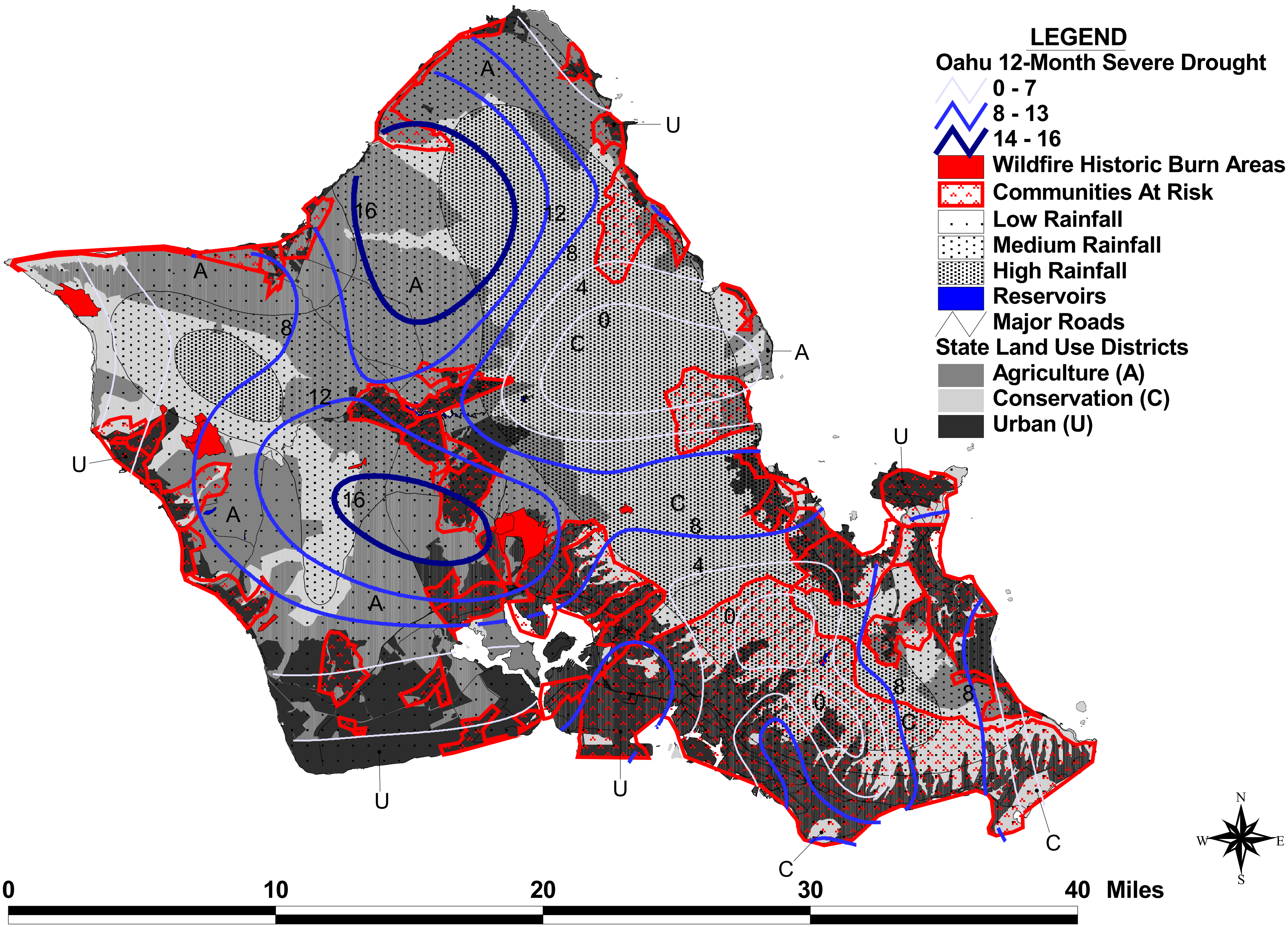


Figure 5.36. Drought Risk Areas
Environment, Public Health, and Safety Sector, City and County of Honolulu
12-Month SPI, Extreme Drought

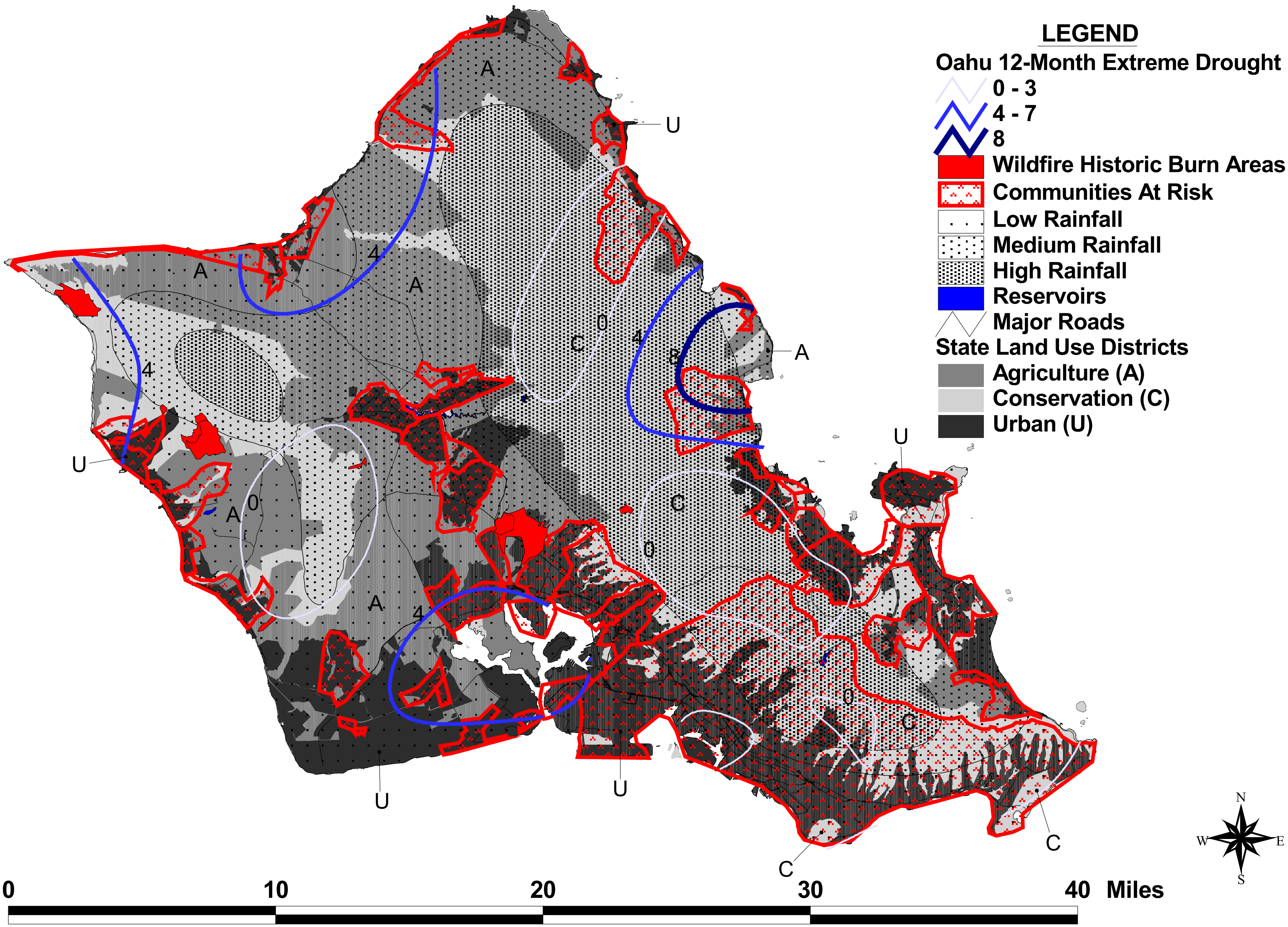


Figure 5.37 Drought Risk Areas
Water Supply Sector, County of Kauai
12-Month SPI, Moderate Drought

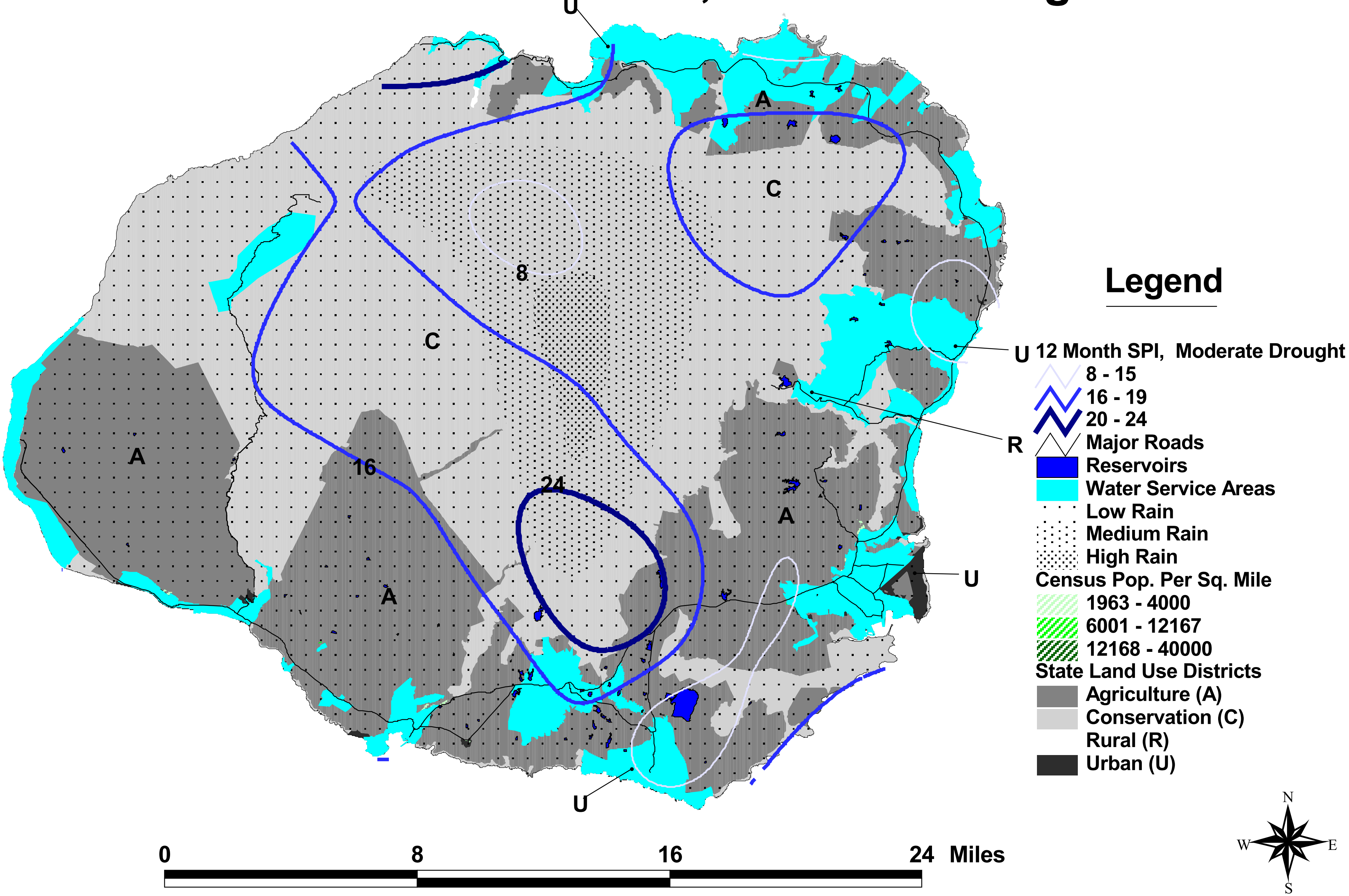


Figure 5.38 Drought Risk Areas
Water Supply Sector, County of Kauai
12-Month SPI, Severe Drought

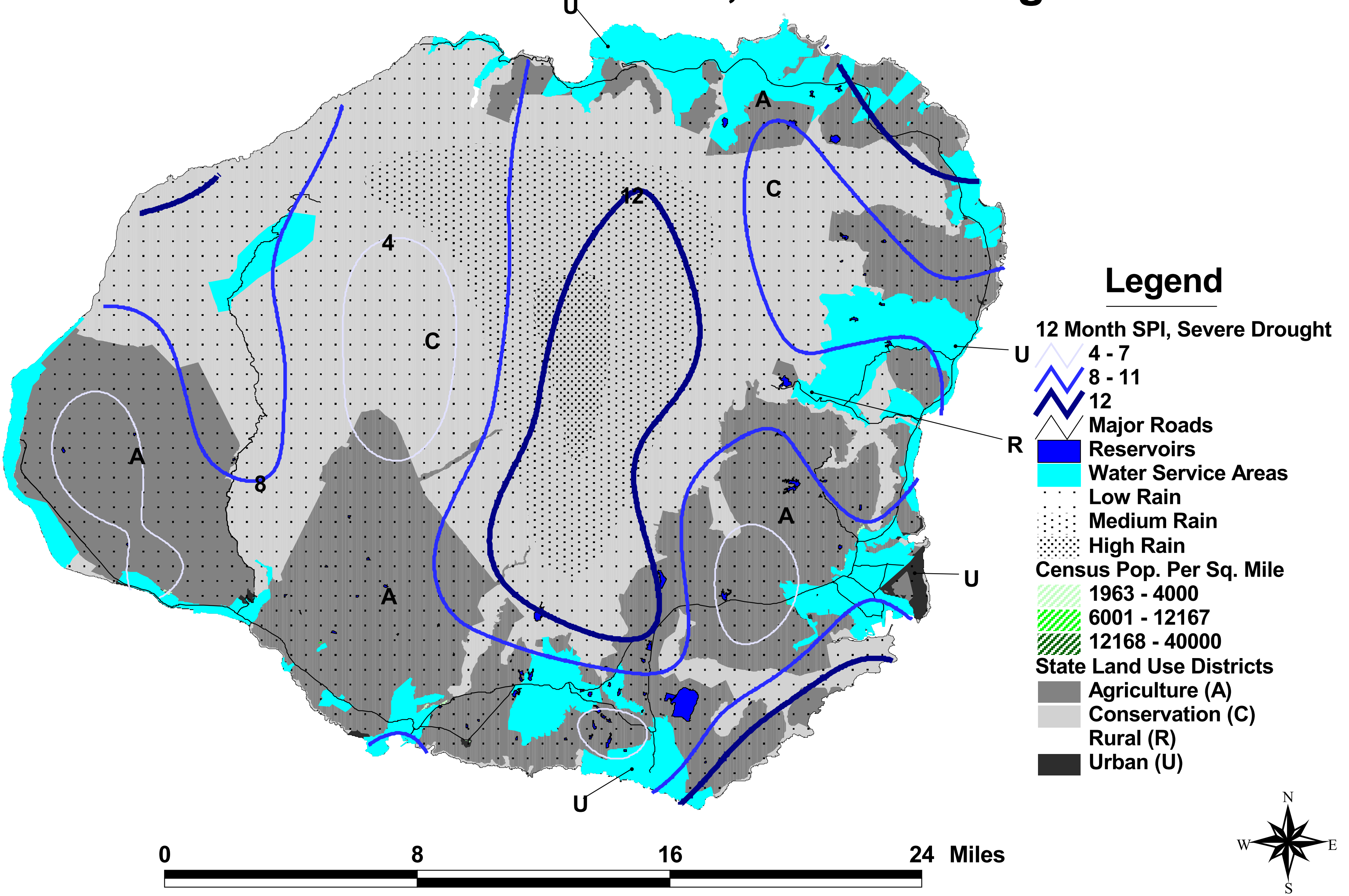


Figure 5.39 Drought Risk Areas
Water Supply Sector, County of Kauai
12-Month SPI, Extreme Drought

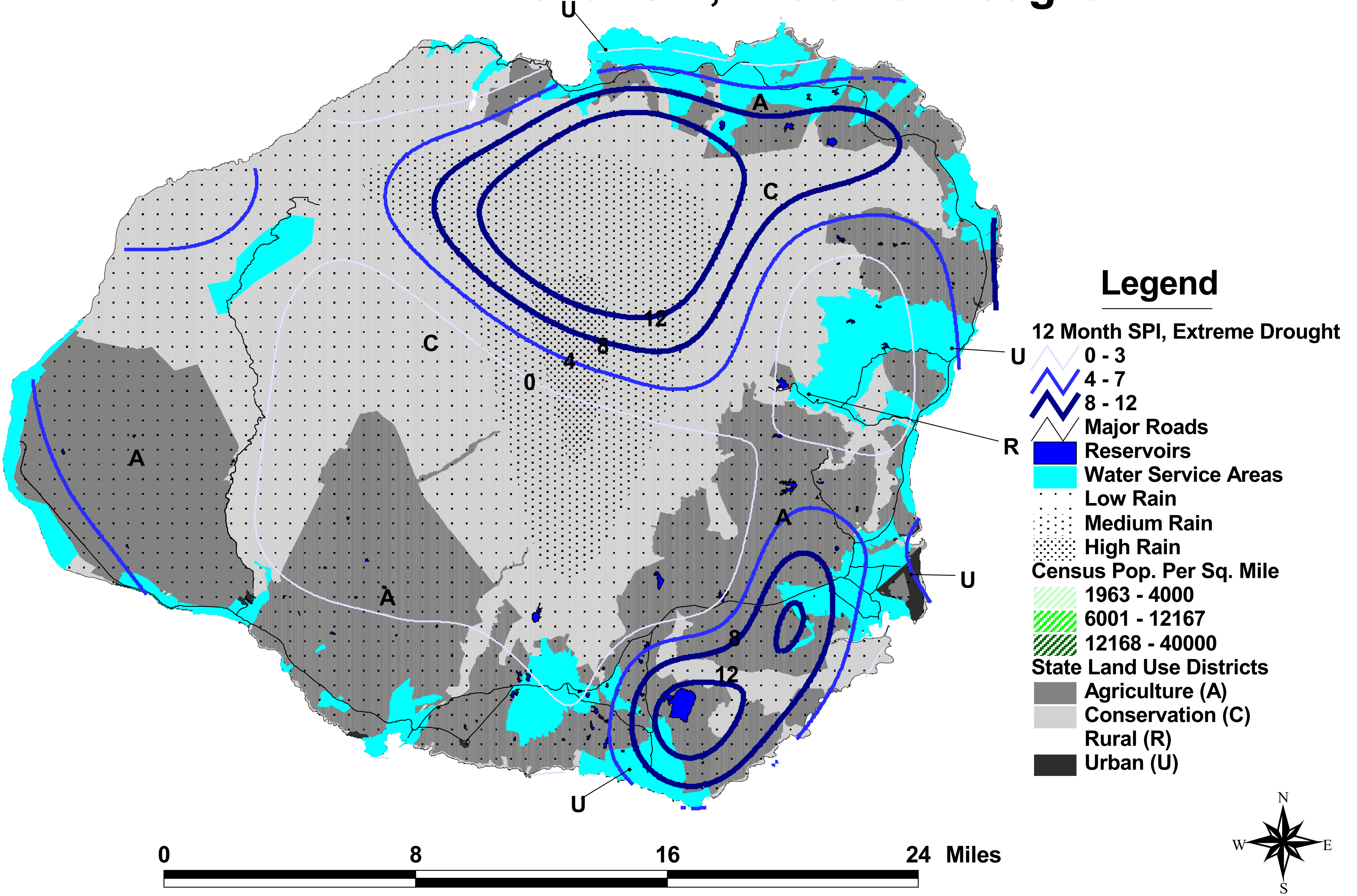
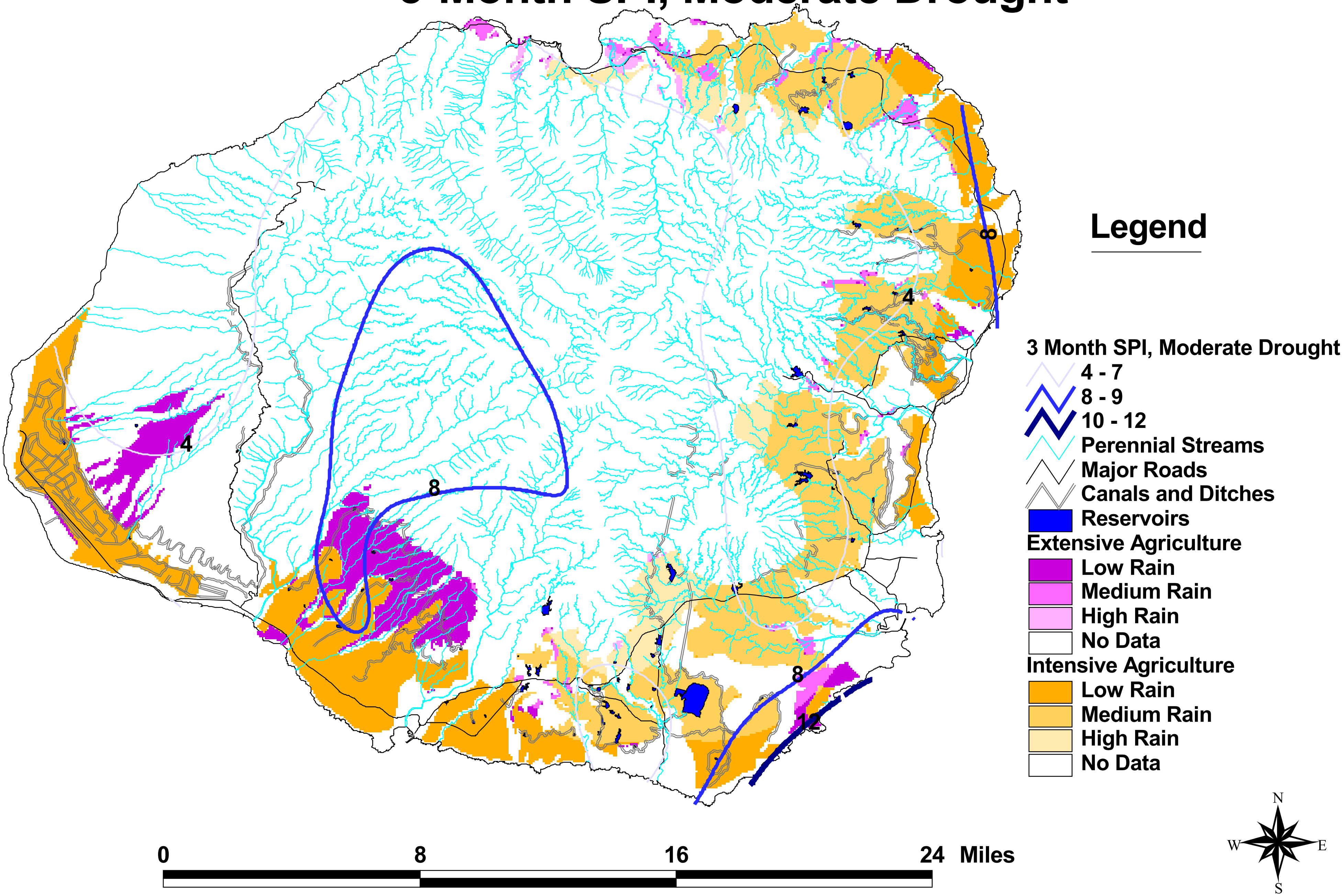


Figure 5.40 Drought Risk Areas
Agriculture Sector, County of Kauai
3-Month SPI, Moderate Drought



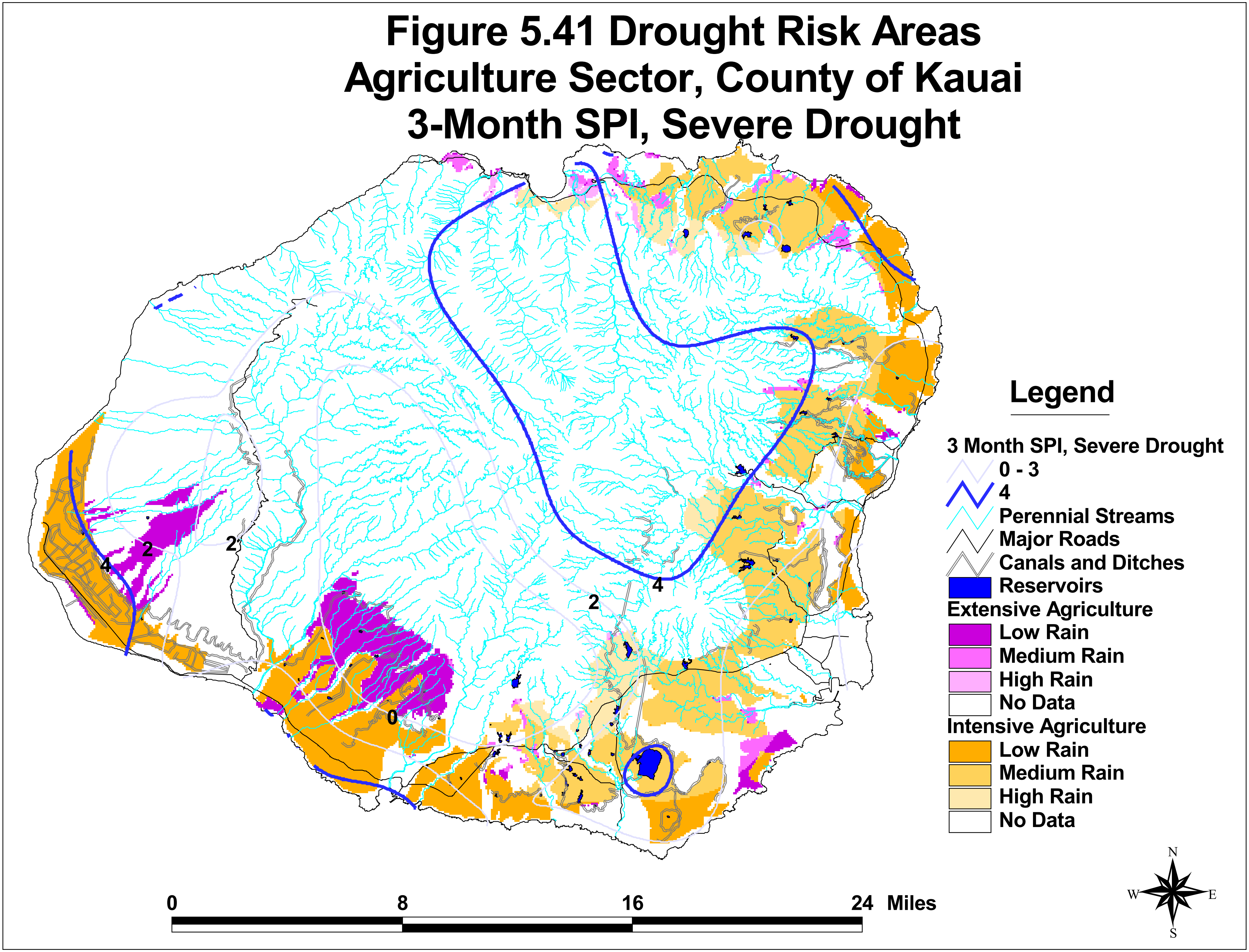


Figure 5.41 Drought Risk Areas
Agriculture Sector, County of Kauai
3-Month SPI, Severe Drought
Legend
3 Month SPI, Severe Drought
0 - 3
4
Perennial Streams
Major Roads
Canals and Ditches
Reservoirs
Extensive Agriculture
Low Rain
Medium Rain
High Rain
No Data
Intensive Agriculture
Low Rain
Medium Rain
High Rain
No Data
0
8
16
24 Miles
N
E
S
W

Figure 5.42 Drought Risk Areas
Agriculture Sector, County of Kauai
3-Month SPI, Extreme Drought

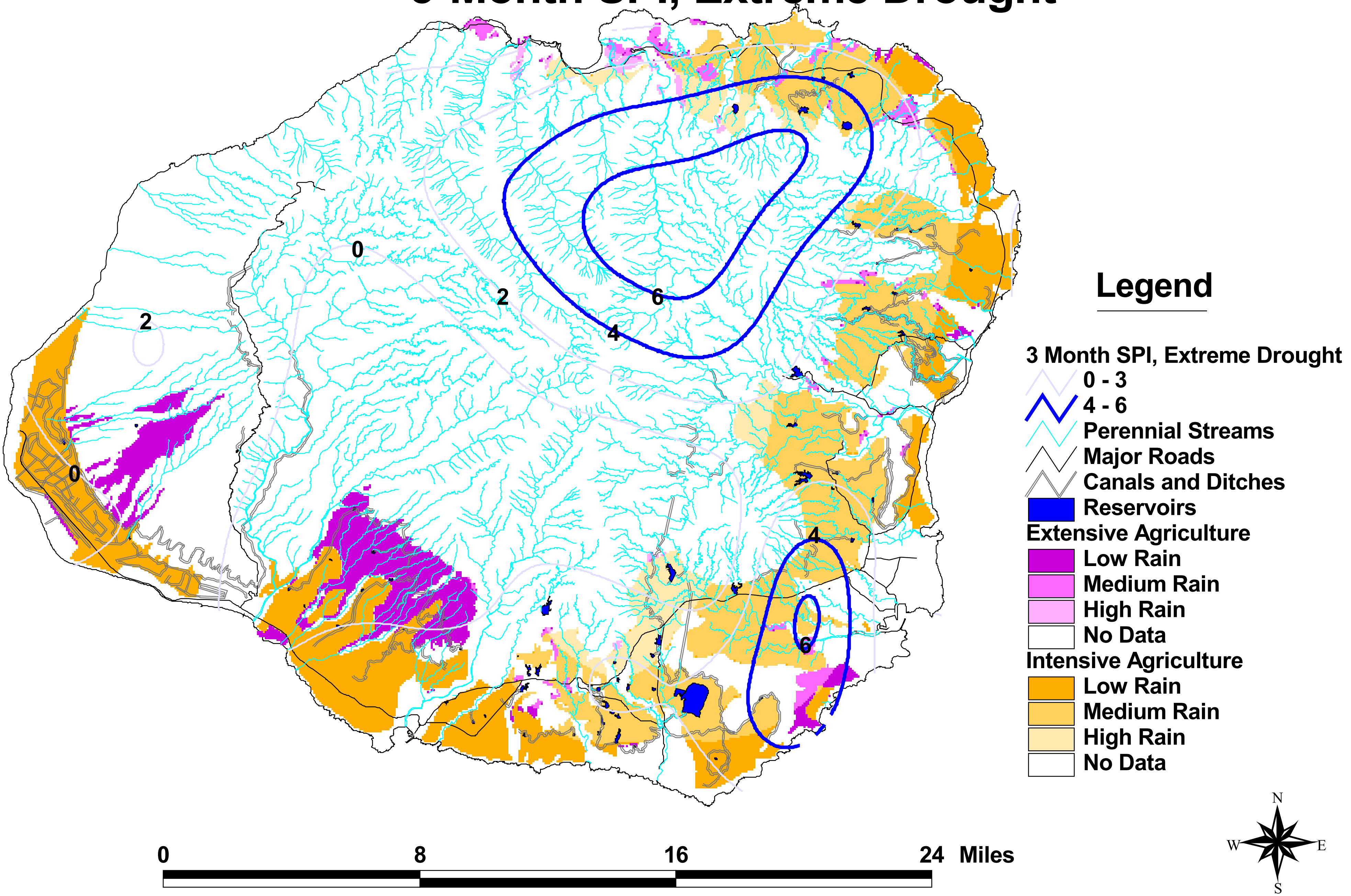


Figure 5.43. Drought Risk Areas
Environment, Public Health, and Safety Sector, County of Kauai
3-Month SPI, Moderate Drought

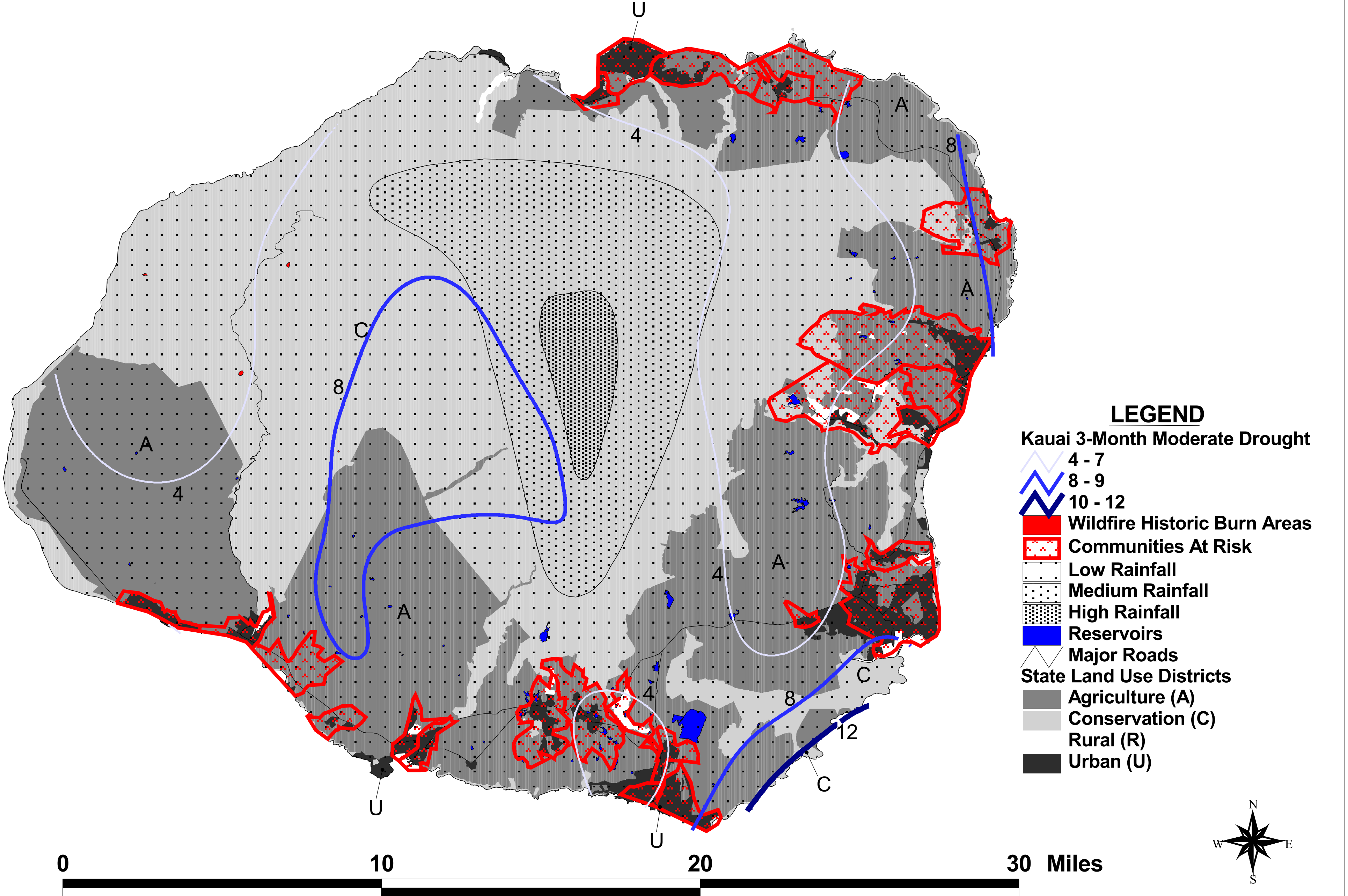


Figure 5.44. Drought Risk Areas
Environment, Public Health, and Safety Sector, County of Kauai
3-Month SPI, Severe Drought

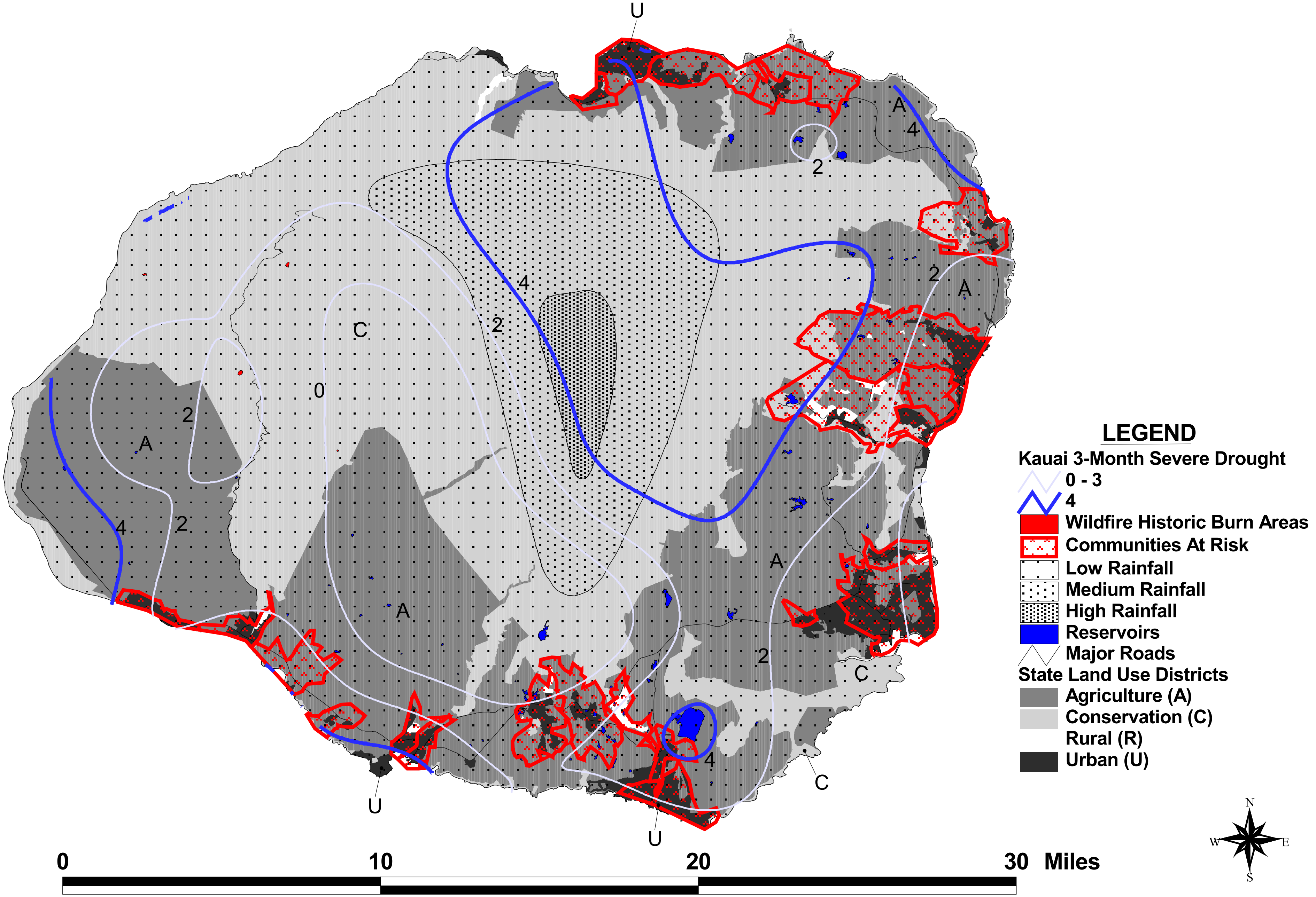


Figure 5.45. Drought Risk Areas
Environment, Public Health, and Safety Sector, County of Kauai
3-Month SPI, Extreme Drought

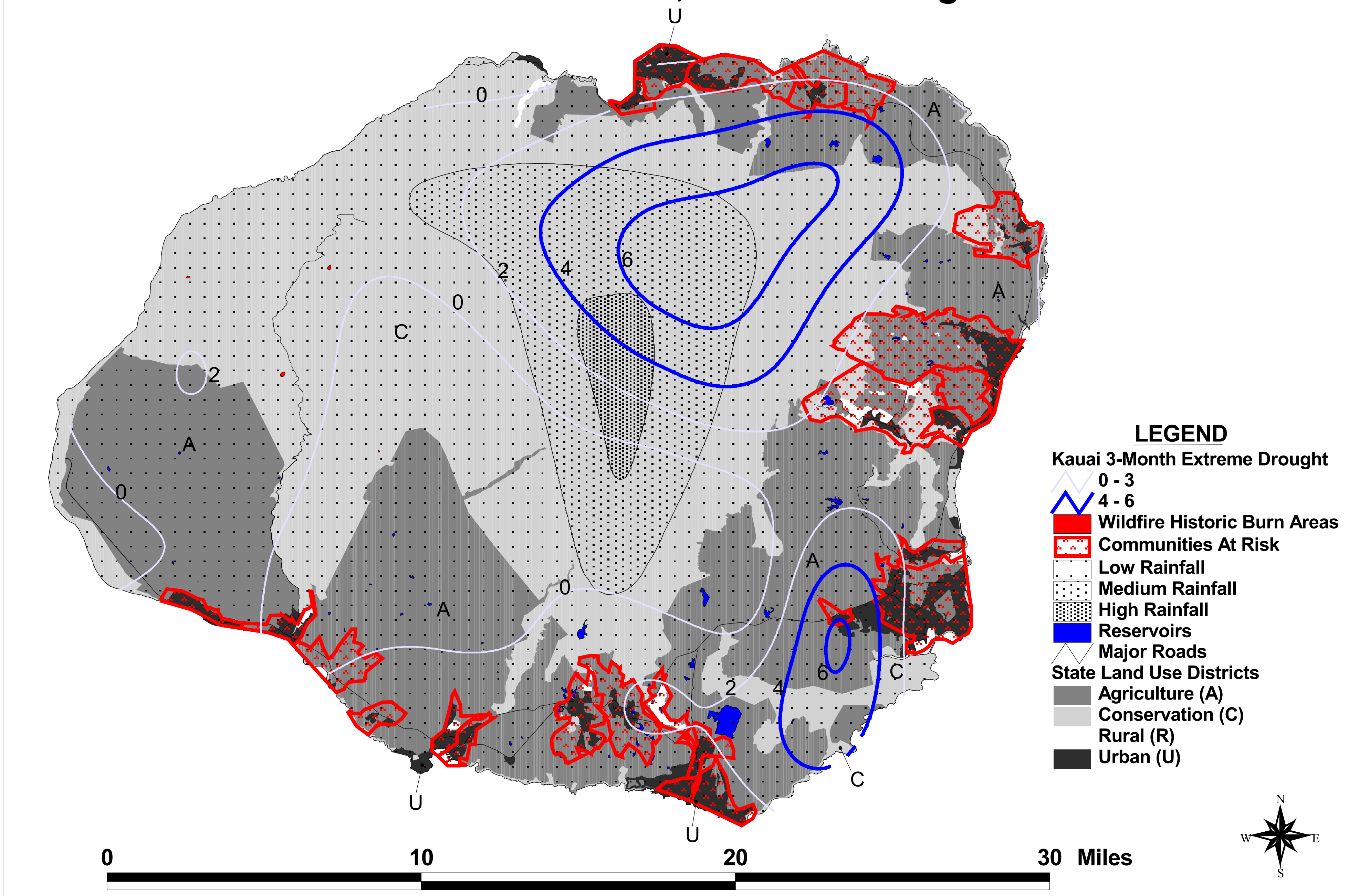


Figure 5.46. Drought Risk Areas
Environment, Public Health, and Safety Sector, County of Kauai
12-Month SPI, Moderate Drought

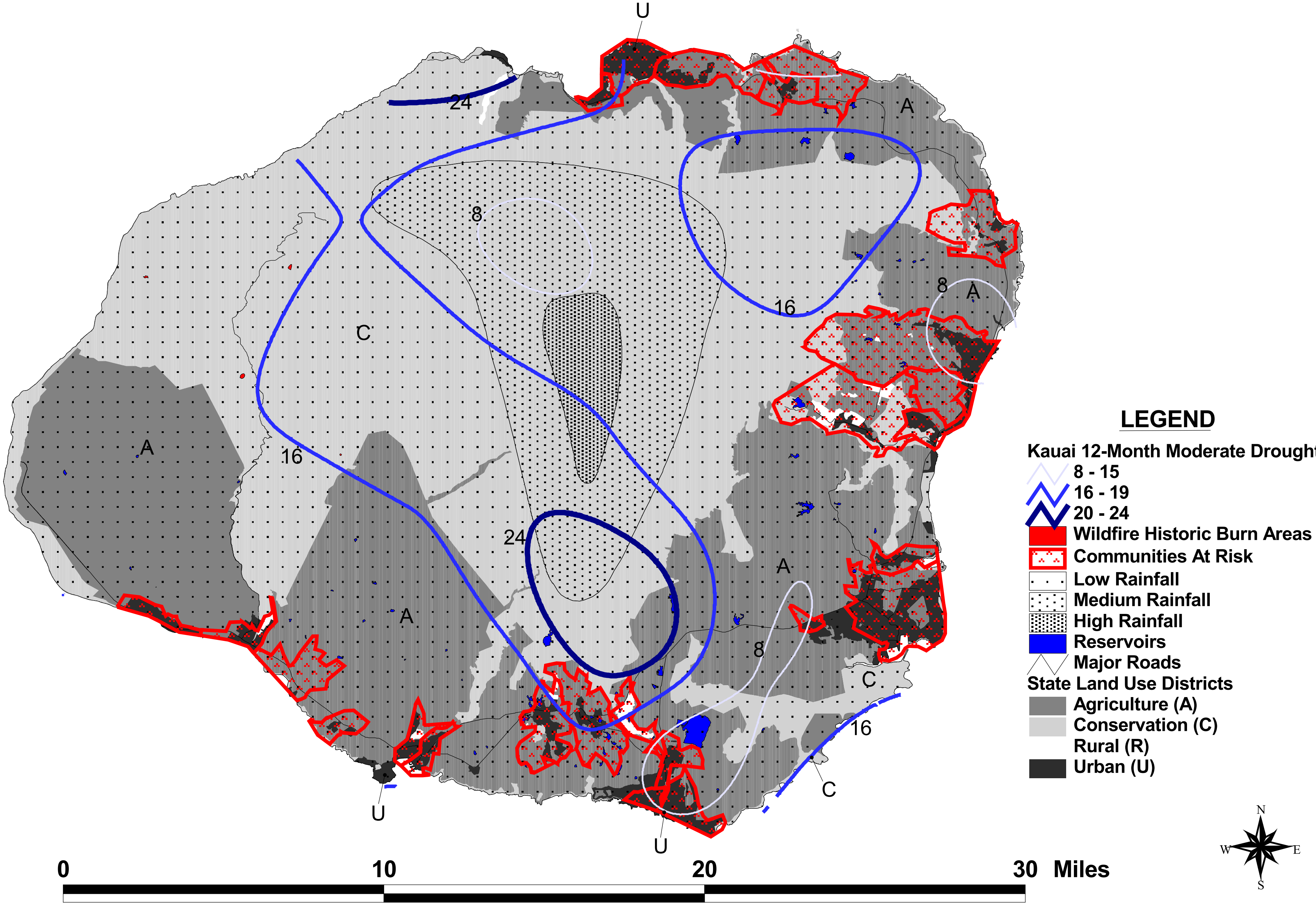


Figure 5.47. Drought Risk Areas
Environment, Public Health, and Safety Sector, County of Kauai
12-Month SPI, Severe Drought

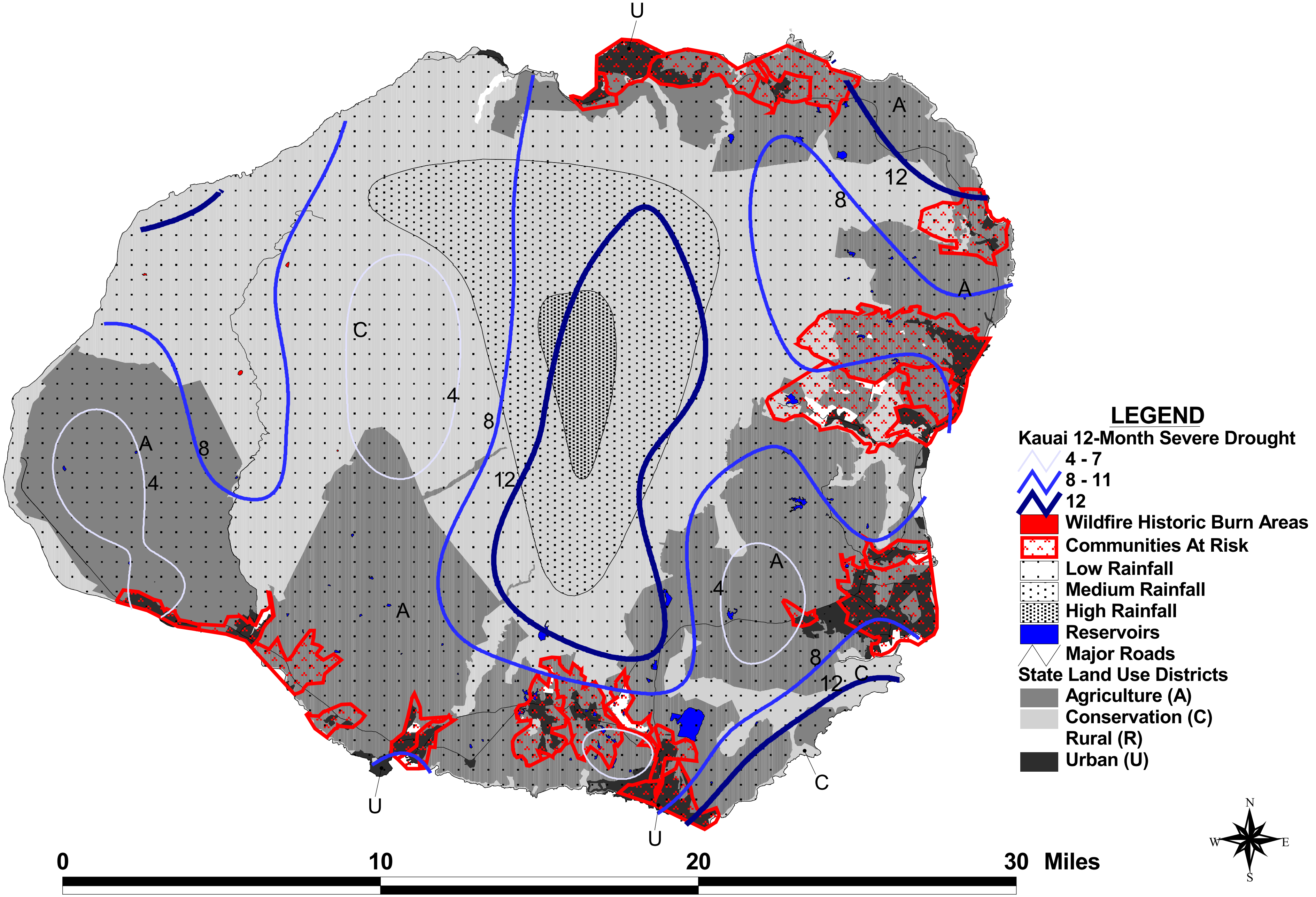
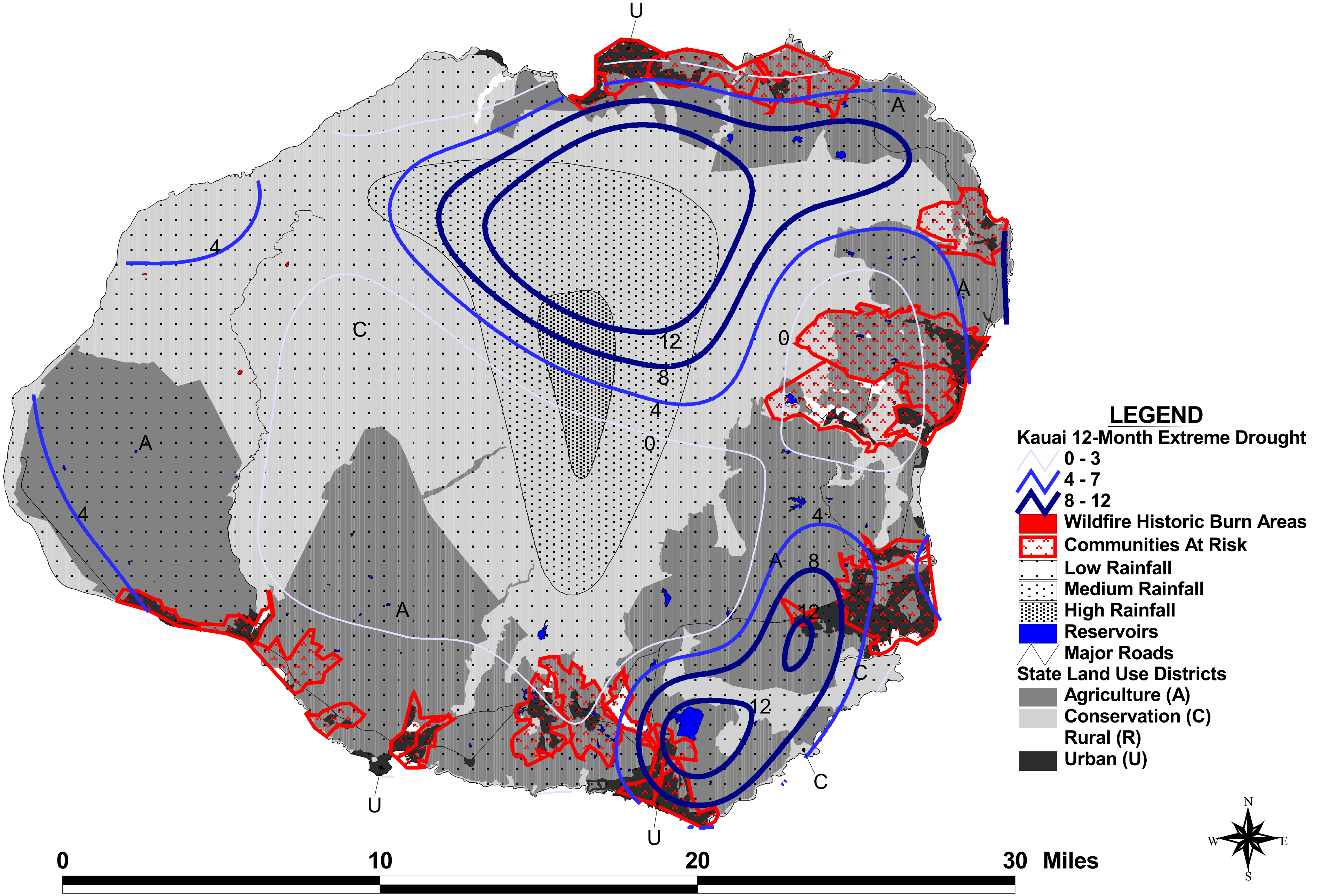


Figure 5.48. Drought Risk Areas
Environment, Public Health, and Safety Sector, County of Kauai
12-Month SPI, Extreme Drought



6. SUMMARY AND CONCLUSIONS

6.1 SUMMARY OF RESULTS

The assessment of drought risk by combining the results of the drought frequency analysis and the vulnerability analysis exposed several similar spatial patterns between the SPI rainfall deficits and the sector's vulnerabilities. Based on common assets and characteristics, the three sectors identified as vulnerable to drought are the water supply, agriculture and commerce, and environment, public health and safety. Three drought stages -- moderate, severe, and extreme -- are considered. The discussion of the results of the drought risk assessment is made county by county, to be in accord with the county hazard mitigation plans. This combined analysis result can then be used to provide some form of early warning of drought impact, the drought severity, and what sector to monitor.

In Section 5, we have identified drought risk areas on the basis of drought severity levels, sector by sector, and county by county. The major results are outlined in Sections 5.3.1.4, 5.3.2.4, 5.3.3.4, and 5.3.4.4. To help illustrate these results, Tables 6.1 to 6.4 lists the key risk areas in each county for each sector.

The drought risk on the three sectors within the County of Hawaii is similar in terms of spatial variations. A common risk area across all three sectors and three drought stages is the western side of the island near Kona, coinciding with low rainfall zones and high drought frequency. For Maui County, the common risk area to the water supply and environment sectors is within the Kula upcountry region. This is shown to exist throughout all three drought stages. For the City and County of Honolulu, Central Oahu appears to be the common risk area in terms of the moderate and severe stages for all three sectors. There is no universal risk area in the County of Kauai across all sectors and drought stages, although a small belt in the southeastern corner of the island does appear to be more vulnerable to some sector and drought levels.

Table 6.1 Drought risk areas for Hawaii County

Drought risk areas for Hawaii County			
Sector	**Drought Stage**		
	Moderate	***Severe***	***Extreme***
Water Supply	Kona, South Point	Kona, Kau	Kona, windslopes of Hamakua
Agriculture and Commence	Kona, windward slope of Hamakua	Kona / western slopes of Mauna Loa near Kealekekua	Kona / Kailua
Environment, Public Health (based on 12-month interval)	Waikoloa, Kona	Kona coast	Kona

Table 6.2 Drought risk areas for Maui County

Drought risk areas for Maui County			
Sector	**Drought Stage**		
	Moderate	***Severe***	***Extreme***
Water Supply	Kula, Kahului, Wailuku, Hana, Lahaina	Kula, Hana	Kula
Agriculture and Commence	Western Molokai, central / south Lanai	South Lanai	
Environment, Public Health (based on 12-month interval)	Kula	Kula, central Molokai	Kula

Table 6.3 Drought risk areas for the City and County of Honolulu

Drought risk areas for the City and County of Honolulu			
Sector	**Drought Stage**		
	Moderate	***Severe***	***Extreme***
Water Supply	Central Oahu (Mililani / Waipio)	Central Oahu	Ewa, Haleiwa
Agriculture and Commence	Central Oahu from Kunia to Helemano	Kunia	North of Helemano
Environment, Public Health (based on 12-month interval)	Central Oahu near Mililani	Central Oahu near Mililani and Kunia	Waipio / Pearl City

Table 6.4 Drought risk areas for the Kauai County

Drought risk areas for the Kauai County			
Sector	**Drought Stage**		
	Moderate	***Severe***	***Extreme***
Water Supply		Koloa, Anahola, Kapaa, Lihue and Poipu	Koloa, Lihue and Poipu
Agriculture and Commence	Lihue, Poipu, Anahola	Kekaha / Mana, Anahola	Southwest of Lihue
Environment, Public Health (based on 12-month interval)		Lihue / Poipu	Lihue, Poipu, and Koloa region

6.2 LIMITATIONS OF THE STATEWIDE DROUGHT RISK AND VULNERABILITY ASSESSMENT

In this study, SPI **time scales** were chosen and applied to each drought impact sector based on the likely impacts of these time scales. Due to time and resource limitations, different SPI time scale scenarios for each impact sector were not investigated. In particular the 12-Month SPI drought frequency analysis was not combined with the vulnerability analysis of the Agriculture and Commerce sector. Furthermore, longer term (> 12-Month SPI) time scales were not investigated. In future studies, it would be interesting to conduct additional risk assessment using several different SPI time scales for each impact sector.

The scope of this study did not involve an in-depth compilation and analysis of drought **impacts**. Any future refinement of this work should include exhaustive research into drought impacts to each of the three impact sectors identified herein. Drought impact analysis would provide valuable insight into the ground-truthing and validation of the conclusions reached in this study.

Rainfall **tercile divisions** were chosen to add a relative low/medium/high rainfall component in the vulnerability analysis. However, due to the extreme variability in annual rainfall normal across the Hawaiian Islands, the tercile divisions may be too coarse to discern appropriate differences in vulnerability within each of the impact sectors. Any further sector vulnerability revisions should include a sensitivity analysis involving selecting the appropriate rainfall-component divisions for each of the drought impact sectors (i.e., how do different annual rainfall groupings affect vulnerability in the Agriculture sector; is it appropriate to group agriculture areas with 20 inches of annual rainfall with agriculture areas with 90 inches of annual rainfall; etc.).

In this project, the adverse effects of drought are expressed conceptually as a product of frequency and the corresponding vulnerabilities. Risk areas are identified for each county and within each sector. Although this approach is sound and viable, results from this approach need to be verified independently with future studies which may be based on other parameters besides drought frequency and vulnerability. As described later in Section 6.4, farmers and ranchers may have their own data and/or ideas as far as drought risk, and gathering such information may provide a means to assess the validity of the results of this study.

At this point, it is worthwhile to mention some caveats of this assessment. In Section 4, the vulnerability analysis of this project is assumed to be a function of several interrelated factors such as population growth and shifts, urbanization, annual precipitation amounts, and others. Areas that appear to be at greater risk tend to coincide with low rainfall zones, high drought frequencies, and sector-based vulnerability regions. Because of climate change, one island or one portion of an island may receive less precipitation in the future while another island or another portion of an island may anticipate increased precipitation. Therefore, risk areas identified from the past climatological rainfall records may not be the same in the next decade(s) in association with global warming and climate change.

The uncertainty in population growth in the future may also limit the applicability of this study. While this study uses the past population density as a base of human vulnerability to the water supply sector, it is not guaranteed that future population growth will remain in the same zones as the current ones. Likewise, agricultural lands will be subject to change in association with natural climate variability/change and human influences. Furthermore, the drought frequency analysis is based on a fixed 30-yr period interval and not as a function of time progression. Therefore, results from the frequency analysis should be viewed as a static feature and not a time-varying phenomenon throughout the past 30 years. In other words, we cannot assess risk trends that appear as a result of future land use change or other activities. In interpreting the drought risk and vulnerability assessment report, all these limitations should be kept in mind.

6.3 ALTERNATIVE METHODS

This project assesses drought risk based on drought frequency and vulnerability. The frequency component of the project is based on the SPI method for measuring precipitation deficits. While this method is suggested by the National Drought Mitigation Center, alternative methods have been used by other agencies. For instance, The Keetch/Byram Drought Index (KBDI) is widely used for wildfire monitoring and prediction as part of the U.S. National Fire Danger Rating System. In the southeast U.S., the KBDI is used as a stand-alone index for operational monitoring areas of increased fire danger. This index indirectly measures the soil moisture content, and depends on daily rainfall amounts, daily maximum temperature, and the annual rainfall. Because of the popularity of the KBDI in the fire community and because only rainfall and temperature measurements are required, the KBDI may be considered as an alternative to rainfall-based SPI method for assessing the wildfire component of the environment, public health and safety sector.

As described in Section 2.4.2, a drought risk study was conducted in Thailand. In that study, risk areas are calculated as a weighted linear combination of a set of meteorological (e.g., rainfall) and physical (e.g., topography) factors. However, some factors (e.g., soil drainage characteristics) are simply not available in Hawaii. It would be interesting to develop a method similar to that study if we had those data. While there are numerous drought studies published throughout the world, literature on drought risk studies is sparse. Therefore, this report is valuable because it provides a unique approach combining the GIS maps of drought frequency and vulnerability to identify drought risk areas in the Hawaiian Islands.

6.4 RECOMMEDATIONS FOR FUTURE STUDIES

6.4.1 DROUGHT FORECASTING

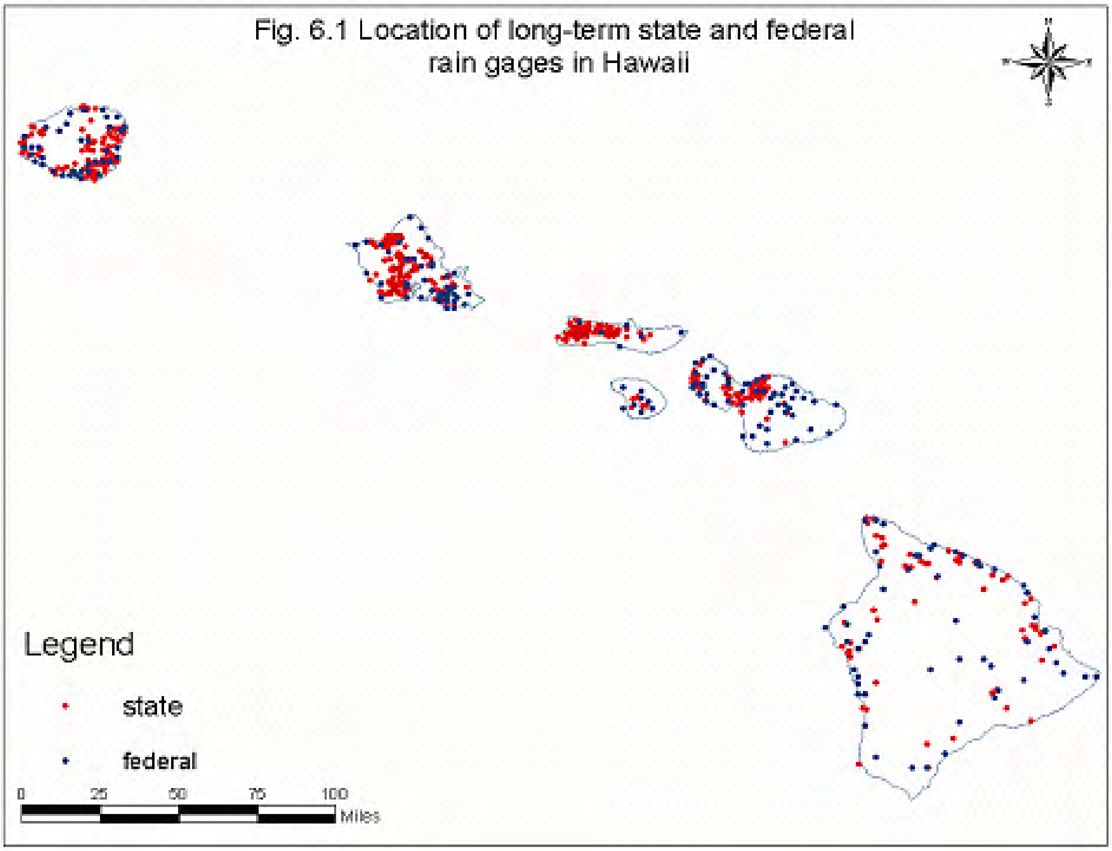
In the past droughts have generally been handled as temporary emergencies, and response actions were taken in a reactive manner. This approach has been changing in recent years. As stated in the Hawaii Drought Plan (2000), "the most important lesson learned in recent years is that the best time to reduce the impacts of drought is before they occur." This calls for a development of models for drought prediction so that a proactive drought management approach can be taken. Accurate forecasts would allow conservation measures before the situation has reached a crisis. Chu and He (1994) developed a sophisticated statistical model, called the canonical correlation analysis, for predicting Hawaii winter rainfall using the Pacific sea level pressures and the Southern Oscillation Index (i.e., a measure of El Niño activity) of the antecedent summer. When tested on an independent data set, their model was able to capture the right phase of winter rainfall prediction 75% of the time.

Current seasonal rainfall forecasting products for Hawaii issued by the NOAA do not include areas where the ground water recharge is high, thus limiting their use to the water supply sector. Furthermore, the forecasting skill is low. With the advance in forecasting technologies in the last few years, such as the ensemble canonical correlation analysis, there is a need to develop a new and improved method for drought forecasting tailored for the Hawaiian Islands. Once developed and tested, the new drought forecasting scheme would be implemented and results would be posted on the Hawaii Drought Council website. This drought forecasting will facilitate an early identification of an impending drought in support of planning and management activities in many climate-sensitive sectors as agriculture, water resource management, public health, and forestry. This in turn will reduce the vulnerability of stakeholders to drought.

6.4.2 ADVANCED DROUGHT FREQUENCY ANALYSIS AND GIS MAPPING

To account for microclimates in Hawaii, it is important to fill the gaps in the spatial rain gage coverage of the federal source so that the resulting maps are truly useful and representative. That is, rain gages from all sources need to be included. In addition to the federal data, the state data, which are unrelated to the federal data, are kept in the Hawaii State Climate Office, at the University of Hawaii-Manoa. The state data are from numerous volunteer observers, such as sugar plantations, ranchers, pineapple companies, and individuals. Figure 6.1 shows the location of the state (20 more years of records) and the federal rain gages. The state gages provide good coverage of central Maui, western Molokai, central Oahu, and most of Kauai.

Figure 6.1 Location of Long-Term State and Federal Rain Gages in Hawaii



Combining the state and federal networks would yield the optimal spatial coverage for analysis. The problem with the state data is that many of them are only available on hard copy. To be useful, they have to be compiled and digitized. In the future, it would be most desirable to improve and increase the accuracy and reliability of the drought frequency analysis by using both the State of Hawaii rainfall records and the data from the NCDC to resolve microclimate variations in Hawaii. Further GIS based impact analysis using the improved data should be performed.

6.4.3 MULTI-YEAR DROUGHT AND RECURRENCE INTERVAL ANALYSIS

Multi-year drought is perhaps the worst kind of drought; because of its long duration, the adverse effect will be felt across all sectors. Hawaii is experiencing a prolonged (4 to 5 years) dry spell. Our current study focuses on drought frequency analysis at 3-month and 12-month intervals. It should be emphasized that risk areas identified are pertinent only to those short-term drought events. It is not known whether the same conclusions drawn in Section 5 can be applied to multi-year drought events. From the historical rainfall data and the SPI method, it would be possible to determine the frequency of multi-year drought and to further analyze both the spatial and temporal variations of the long-duration drought events.

Also of interest would be the investigation of the recurrence interval (sometimes called the return period) of multi-year drought events. The return period is the average time interval between the occurrence of a given event and the next one of equal or greater value. In the arenas of other natural disasters such as hurricanes and flooding, the return period analysis constitutes an essential part of hazard mitigation planning (e.g., Neumann, 1987; Chu and Wang, 1998). Because the prolonged dry spells are extreme events, extreme value distributions and the method of maximum likelihood shall be used.

6.4.4 ANALYSIS OF DROUGHT PATTERNS AND SEVERITY DURING EL NINO AND LA NINA YEARS

It is known that a dry winter and possibly a dry spring in Hawaii usually follow the onset of El Nino. The question arises as to whether there are any preferred drought patterns during an El Nino cycle. In other words, would certain areas of an island be more susceptible to El Nino-induced drought? Another question would be what is the level of drought severity associated with an El Nino? In terms of the different drought stages, would moderate or severe drought occur more often during climate extremes? Given that the return period of El Nino is approximately three to five years, it would be useful to conduct a study of this kind so that we may better anticipate drought patterns and severity in the future once an El Nino is developing. A similar study can be conducted for the La Nina events.

In Section 3.1, it was mentioned that the Pacific Decadal Oscillation (PDO) was in the negative phase during 1946 to 1977 and in the positive phase thereafter. A statistically significant and negative correlation was also found between the PDO index and the Hawaii rainfall index during the last century. Thus, when the PDO was in the positive (negative) phase, Hawaii rainfall tended to be below (above) normal. Given this robust signal, it would be of interest to investigate the changes in drought frequency/patterns during different phases of the PDO as a guide for future long-term drought risk management.

6.4.5 DROUGHT IMPACT STUDIES

The current study has indicated areas where there seems to be strong impacts from drought and wildfires. Unfortunately, the spatial data do not provide a representation of the severity of the impacts experienced by residents living in these locations. For example, a farmer in an area of drought may have relied on the use of an irrigation system with an interrupted source of water and may not have experienced much impact from the drought, while a cattle rancher may have been without any suitable drinking water for his herd and lost several of the animals. Understanding exactly how people are impacted by the extremes in climate variation may provide ideas for reducing the impacts to these people.

It will be important to engage in further analysis to improve our understanding of the findings developed in this first phase of the drought and wildfire risk and vulnerability analysis. Agencies involved in drought response and relief assistance have typically not kept good records. An accurate accounting system of loss data due to droughts does not seem to exist. In discussions with the USDA Farm Services Agency, it seems that federal requirements are highly variable such that some losses that may have qualified by the standard of previous disasters will not qualify during the respective drought. This lack of standardization by agencies in reporting and distributing relief assistance makes it difficult to quantify or even qualify the degree of drought severity from event to event. Therefore, it will be important to gather and develop qualitative information and anecdotal reports.

One means of gathering such information is through discussions and interviews with the farmers, ranchers, and representatives of industries impacted by the previous droughts. Often, farmers and ranchers have collected data to make their business decisions, such as culling herds or time for planting. Complicating the matter, through surveying extension agents and agencies, it was found that there is no standardized method for data collection. Some of the prices used for analysis are based on market factors and differ from place to place. Without deeper discussions and analysis of qualitative impact data, it will be nearly impossible to truly understand the severity of the drought and its impacts on those affected. Overall, these analyses are important as a quantification of and substantiation for funding to reduce the loss and suffering from these extreme climatic variations.

In this century, the numbers and severity of climate change events have been projected to increase. Without improving our understanding of these events and finding adaptive strategies to reduce impacts, the State of Hawaii could be severely affected in terms of economic losses, and more importantly, in terms of loss of life and the overall quality of life in Hawaii.

Many other tropical Pacific islands have similar problems, mainly, increasing population and demand for freshwater and large, natural variability in rainfall. It is hoped that the unique approach developed here is valuable not only to Hawaii but to other tropical Pacific islands in better coping with future drought hazards.

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