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Assessing Vulnerability to Agricultural Drought: A Nebraska Case Study

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Abstract

Recent drought events in the United States and the magnitude of drought losses indicate the continuing vulnerability of the country to drought. Until recently, drought management in many states, including Nebraska, has been largely response oriented with little or no attention to mitigation and preparedness. In 1998, Nebraska began to revise its drought plan in order to place more emphasis on mitigation. One of the main aspects of drought mitigation and planning is the assessment of who and what is vulnerable and why. This paper presents a method for spatial, Geographic Information Systems-based assessment of agricultural drought vulnerability in Nebraska. It was hypothesized that the key biophysical and social factors that define agricultural drought vulnerability were climate, soils, land use, and access to irrigation. The framework for derivation of an agricultural drought vulnerability map was created through development of a numerical weighting scheme to evaluate the drought potential of the classes within each factor. The results indicate that the most vulnerable areas to agricultural drought were non-irrigated cropland and rangeland on sandy soils, located in areas with a very high probability of seasonal crop moisture deficiency. The identification of drought vulnerability is an essential step in addressing the issue of drought vulnerability in the state and can lead to mitigation-oriented drought management.

Keywords: vulnerability assessment, drought, mitigation, geographic information systems, agriculture.

1. Introduction

Drought affects virtually all climatic regions (Wilhite, 2000a) and more than one-half of the earth is susceptible to drought each year (Kogan, 1997). In the United States, drought is also a persistent climatic problem. Examinations of the spatial patterns of droughts in the contiguous U.S. show a tendency for persistent drought in the central to northern Great Plains and Rocky Mountains (Walsh *et al.*, 1982; Karl, 1983; Karl *et al.*, 1987; Soule, 1992). Nebraska, located in the central U.S. and being a part of the Great Plains physiographic region, has a long history of droughts of various geographic extent, severity, and duration (Weakly, 1943, 1965; Drew, 1974; Lawson *et al.*, 1980; Wilhite, 1981; Stockton and Meko, 1983; Muhs and Holliday, 1995; Woodhouse and Overpeck, 1998).

Hewitt (1997) reported that, throughout the world, drought ranks first among natural disasters in numbers of persons directly affected. The impacts of drought depend largely on societal vulnerability at the time when drought occurs. Blaikie *et al.* (1994) showed that the risk of possible disaster is a combination of a hazard and societal vulnerability. In the last two decades, losses from drought events significantly increased without documented evidence of increased number or severity of droughts (Wilhite, 2000b). Riebsame *et al.* (1991) stated that losses from the 1987–89 U.S. drought illustrated the continuing vulnerability of many natural resources and economic sectors to drought. The losses from the 1988 drought alone have been estimated at more than $39 billion ($52 billion in 2000 dollars). Awareness of this problem has led to increasing attention to the issue of drought vulnerability in recent years (Wilhite, 1993, 2000b; World Food Program, 1996; Keenan and Krannich, 1997; Downing and Bakker, 2000).

Many farmers partially mitigate drought impacts through crop selection, irrigation, and tillage practice (Waltman, 1999). To date, on the state level, the emphasis of disaster management has been largely on response and recovery from drought, with little or no attention to mitigation, preparedness, and prediction and monitoring (Wilhite, 2000b). In recent years, increased losses from droughts suggest growing societal vulnerability to drought. There has also been a shift in drought management from a reactive, crisis management approach to a proactive, risk management approach, which requires planning between periods of drought (Wilhite, 1992, 2000b). One of the main aspects of drought planning and mitigation includes vulnerability assessment (Wilhite, 1993, 1997, 2000b; Knutson *et al.*, 1998), since vulnerability plays a critical role in the relationship between a hazard and society.

In 1998, at the Nebraska Climate Assessment and Response Committee (CARC) annual meeting, the National Drought Mitigation Center (NDMC) recommended revising the State's drought plan by placing greater emphasis on drought mitigation. In 1998, two subcommittees formed by the CARC completed a limited assessment of drought vulnerability. The research presented here stems from the NDMC recommendations and focuses on drought vulnerability assessment for the agricultural sector of Nebraska. This paper presents a methodology for Geographic Information Systems-based assessment and mapping of agricultural drought vulnerability in Nebraska and the results of this assessment.

The purpose of assessing vulnerability is to identify appropriate actions that can be taken to reduce vulnerability before the potential for damage is realized. The need for vulnerability assessment is noted in the scientific literature (Downing, 1991; Anderson, 1994; Eastman *et al.*, 1997; Hewitt, 1997; Keenan and Krannich, 1997; Downing and Bakker, 2000). However, because of the complexity of the issue of vulnerability, assessments are commonly subjective and vary between regions and hazards. Downing and Bakker (2000) state that vulnerability is a relative measure, and the analyst must define its critical levels. Mapping vulnerability to drought is a challenging task, because drought is also a very complex and the least understood phenomenon, which lacks universal definition and onset criteria (Wilhite, 1993, 2000b). Factors influencing drought vulnerability are numerous, and their inclusion may depend on data availability. Despite limitations, available information on regional drought vulnerability could aid decision makers in identifying appropriate mitigation actions before the next drought event and lessen impacts of that event. With a map of drought vulnerability, decision makers can visualize the hazard and communicate the concept of vulnerability to agricultural producers, natural resource managers, and others. The goal of this study was to develop a method for assessing vulnerability to agricultural drought using geographic processing techniques. The objectives were to:

1. Identify key factors that define agricultural drought vulnerability in Nebraska;
2. Evaluate the weight of the factors that contribute to drought risk and vulnerability;
3. Classify and map agricultural drought vulnerability.

This paper also addresses the concepts of vulnerability, since assessing societal vulnerability requires a good understanding of underlying causes of vulnerability as well as its dynamic nature.

1.1. Setting

Nebraska is located in the central United States, in the physiographical region known as the Great Plains (Figure 1). The absence of mountainous barriers on the north and south borders of Nebraska allows polar and tropical air masses to have a great influence. The Rocky Mountains form a barrier on the west that keeps Nebraska in a rain shadow relative to the Pacific air masses. The state's climate is characterized by subhumid (in the east) to semiarid (in the west) conditions, great annual temperature variations, highly variable precipitation, and several prominent natural hazards (e.g., droughts, floods, tornadoes, and hail). Evapotranspiration rates are high and in most of the state potential evapotranspiration exceeds precipitation. The geographical location of the state and an east-to-west elevation gradient (about 1000 meters) determine several climatic gradients: an east-to-west decrease in mean temperatures, an east-to-west decrease in mean precipitation and an east-to-west increase in potential evapotranspiration. These gradients mainly determine the state's environmental and land use characteristics. Agricultural settlement in Nebraska proceeded from east to west – along the decreasing precipitation gradient and toward marginal environments with more variable precipitation (Riebsame *et al.*, 1991).

Figure 1. The continental United States and study area—state of Nebraska.

2. Background

2.1. Concepts of Vulnerability

The use of the terms "vulnerable" and "vulnerability" is often vague and often equated with "poor" and "poverty" (World Food Program, 1996). However, that is not always the case. The most basic definition of vulnerability is derived from its Latin root *vulnerare* meaning "to wound," and therefore vulnerability is "the capacity to be wounded" (Kates, 1985). The concepts and definitions of vulnerability have been analyzed by Timmerman (1981), Kates (1985), Chambers (1989), Downing (1991), Anderson (1994), Blaikie *et al.* (1994), Bohle *et al.* (1994), Downing and Bakker (2000) and others. Most definitions of vulnerability contain a common thread. They all agree that vulnerability shows the degree of susceptibility of society to a hazard, which could vary either as a result of variable exposure to the hazard, or because of coping abilities. Coping abilities, according to Downing and Bakker (2000), include protection and mitigation.

Downing (1991) and Dow (1993) presented reviews of factors contributing to societal vulnerability. For example, Dow (1993) stated that among vulnerability factors are characteristics of the environment, individuals, and society. Examples of factors contributing to vulnerability include economics, technology, social relations, demographics and health, biophysics, individual perception and decision making, and institutions. Some factors, such as economics, technology and infrastructure, are better understood. Individual and societal factors are more difficult to understand and conceptualize. Those factors add to the complexity of identifying vulnerabilities.

Vulnerability has a time dimension. As noted by Downing and Bakker (2000) and Wilhite (2000b), vulnerability changes over time, incorporating social responses as well as new rounds of hazardous events. Since it is damage to livelihood and not just life and property that is at issue, the more vulnerable groups are those that also find it hardest to reconstruct their livelihoods following the disaster. They are, therefore, more vulnerable to the effects of subsequent hazard events (Blaikie *et al.*, 1994). Vulnerability constantly changes because of changes in technology, population behavior, practices, and policies. Downing and Bakker (2000) indicate that even from season to season, vulnerability can vary from extreme crisis to complete safety.

Vulnerability is closely correlated with human infrastructure and socioeconomic conditions. As a rule, the poor suffer more from hazards than the rich, although poverty and vulnerability are not always correlated. Drought vulnerability is different for different individuals and nations. In developing countries, drought vulnerability constitutes a threat to livelihoods, the ability to maintain productive systems, and healthy economies. In developed economies, drought poses significant economic risks and costs for individuals, public enterprises, commercial organizations, and governments (Downing and Bakker, 2000).

Droughts are viewed as primarily atmospheric phenomena. However, the importance of droughts is their negative impacts on society (e.g., social, economic, and environmental damage). Downing and Bakker (2000) stated that hazardous weather differs from normal weather by its potential to do damage, and not by its physical or statistical properties. Blaikie *et al.* (1994) showed that the *risk* of possible disaster is a combination of *hazard* and *vulnerability.* Therefore, the level of risk that the hazard poses to people is directly related to societal vulnerability. Downing and Bakker (2000) also stated that vulnerability largely defines drought risk rather than the frequency and severity of weather anomalies on their own. In order to lessen the impacts of drought, societal vulnerability must be reduced. However, more effort has been spent on predicting and monitoring climatic, hydrological and biological conditions, than on identifying societal vulnerabilities (Downing and Bakker, 2000). Keenan and Krannich (1997) emphasized that vulnerabilities associated with drought are linked more closely to the social context in which water scarcity occurs, rather than with just the physical and climatological events that contribute to scarcity. Attempts to more effectively address the need to plan for drought will fall short unless differential vulnerability is recognized and taken into account as a key consideration in the overall planning effort.

2.1.1. Spatial nature of drought and vulnerability: Assessment and mapping

Droughts, like other natural phenomena, have spatial and temporal dimensions. In assessing drought, many researchers have used the capability of Geographic Information Systems (GIS) to store and analyze large volumes of remotely sensed data. The recent approaches to drought monitoring found in the literature are based primarily on the use of the Normalized Difference Vegetation Index (NDVI), obtained from processing AVHRR data from NOAA satellites (Tucker and Goward, 1987; Kogan, 1990; Peters *et al.*, 1991; Lozano-Garcia *et al.*, 1995; Liu and Kogan, 1996). The main advantages of AVHRR data are their applicability to large area analysis, high temporal resolution for evaluation of dynamic vegetation characteristics, computer compatibility of remotely sensed data, and the extension of the sensitive spectral region into wavelengths that provide effective vegetation discrimination (Walsh, 1987).

The use of GIS for integrating data from different sources was found essential in many drought studies (Lourens, 1995; Chang *et al.*, 1997; De Jager *et al.*, 1997; Ghosh, 1997; Reed, 1993; Thiruvengadachari and Gopalkrishna, 1993; Matthews *et al.*, 1994). For example, Reed (1993) analyzed landscape/drought interaction in Kansas. Land use, soil and slope data were combined to form landscape regions. Each of the variables and their combinations were analyzed with respect to the drought-affected regions to identify landscape elements vulnerable to drought damage. Thiruvengadachari and Gopalkrishna (1993) developed a drought proneness modeling system. A weighting model was used to show relative drought proneness of Karnataka State, India. Independent and equally weighted variables used in the model included percentage irrigation support, percentage of rainfed area, percentage of forested area, and normal seasonal rainfall for each district. Matthews *et al.* (1994) developed a GIS-based methodology to assess the possible impacts of climate change on the susceptibility of soils to drought in Scotland. The maps of soil drought susceptibility identified areas with increased risk of yield reductions due to periodic drought stress, under a global warming condition.

Mapping of vulnerability began in the late 1970s (Currey, 1978). However, a large increase in the number of studies on assessment of spatial vulnerability occurred in the last decade. Two main reasons, perhaps, lead to this increase. The first is the recognition of the importance of vulnerability in hazard assessment and disaster management. The second is the availability of GIS technology, which made it possible to integrate data of different types (e.g., biophysical and socioeconomic) and from different sources, analyze data, and present results in a timely and appropriate manner for environmental and agricultural decision making.

Probably the largest amount of literature on vulnerability assessment and mapping is published by the World Food Program (1996). Their work mostly targeted vulnerability to food insecurity and famine in developing countries. In 1996, WFP published guidelines for vulnerability analysis and mapping, which were primarily based on the work done by Borton and Shoham (1990). The guidelines provided start up support to WFP country offices for analyzing the vulnerability of target populations to food insecurity and coping capability, and for presenting the analysis with digital maps. Vulnerability assessment data and maps contributed to a better targeting of areas prone to or affected by disaster. They also provided inputs on relief and development activities and coping mechanisms (World Food Program, 1996).

As a part of the larger UNEP project on GIS-based, environmental risk assessment, Eastman *et al.* (1997) reviewed the procedures for assessment and mapping of food security in West Africa. The study was focused on the spatial nature of vulnerability and described the approaches undertaken by different countries for vulnerability assessment. For example, in Zambia's vulnerability assessment (USAID/FEWS, 1994), a composite index of vulnerability was based on the following three broad groups of factors: crop risk (e.g., average length of growing season; share of drought-resistant crops), market access, and coping strategies.

3. Data and Methodology

3.1. Identification of Drought Vulnerability Factors in Nebraska

Factors that influence drought vulnerability are numerous. Since the focus of this study was on assessing societal vulnerability to agricultural drought, the identification of key vulnerability factors was based on their significance for agricultural sector. Analysis of drought literature, suggestions from Nebraska's climate and agriculture specialists, and data availability formed a fundamental assumption underlying this methodology that two biophysical factors, climate and soils, and two social factors, land use and irrigation, were the most significant factors of agricultural drought vulnerability in Nebraska.

3.1.1. Climate

Agroclimatological factors of vulnerability were defined by synthesizing climate and crop data (Wilhelmi, 1999). Climate data (e.g., monthly precipitation) were obtained from the High Plains Regional Climate Center at the University of Nebraska–Lincoln (Figure 2).

Agricultural crop statistics data were obtained from National Agricultural Statistic Service (NASS) (1997). The assumption underlying the approach taken in this study was that the best characterization of the climatology of the State from the drought vulnerability perspective is the probability of seasonal crop moisture deficiency. Seasonal crop water use thresholds for well-watered crops (e.g., corn, soybean and sorghum) were estimated using the evapotranspiration (*ET*) mathematical model developed by Hubbard (1992). For wheat and grass, *ET* values were estimated using water use efficiency and crop yield (Musick and Porter, 1990). Historical yield data were used to determine the economically successful threshold for wheat. Thresholds determined for the crops in the State were used to calculate area-weighted mean *ET* for the combination of crops in every county. Threshold values and long-term precipitation data were used in a SAS

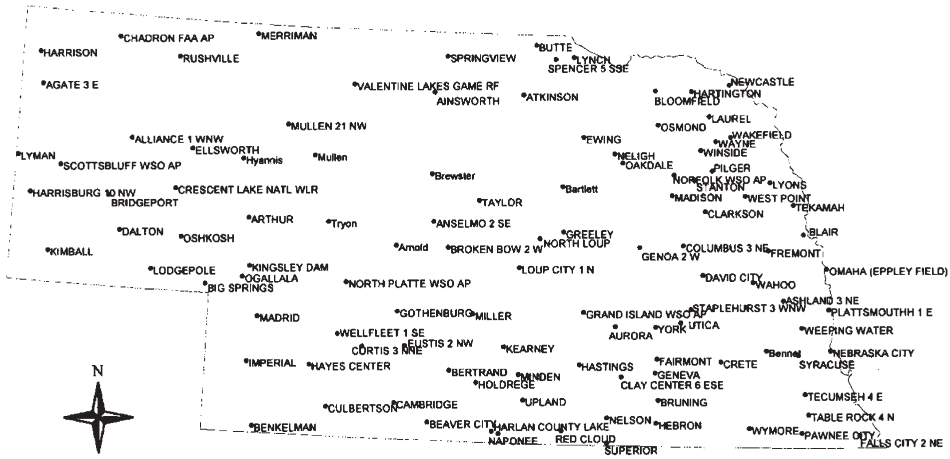

Figure 2. Locations of National Weather Service's Cooperative Observer Network weather stations used in this study.

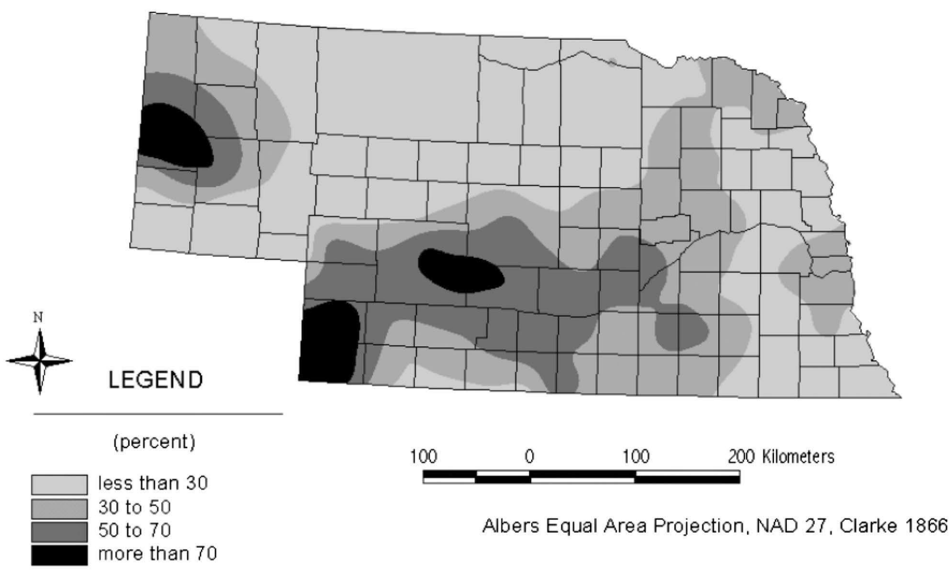

Figure 3. Spatial variation in probability of the seasonal crop moisture deficiency in Nebraska. Spatial interpolation was performed using ArcView Spline. Spatial resolution = 200 meters.

statistical program (*SAS* Institute, Inc.) to estimate statistical probabilities of seasonal crop moisture deficiency by Cumulative Distribution Function. Probability values were assigned to 112 weather stations in Nebraska and point data were spatially interpolated using ArcView (Environmental Systems Research Institute, Inc., Redlands, CA). The map of probabilities of seasonal moisture deficiency is presented in Figure 3.

3.1.2. Soils

Soil climate regimes in Nebraska range from Udic in eastern Nebraska to Aridic in the Sand Hills region, north-central Nebraska. The Udic moisture regime is common to the soils of humid climates that have well-distributed rainfall, or that have enough rainfall in summer so that the amount of stored moisture plus rainfall is approximately equal to or exceeds the amount of evapotranspiration. Soils with an Aridic moisture regime are typical for arid climates; however, some are present in semiarid climates (Soil Survey Staff, 1975). The geographic pattern of soil water-holding capacity is important for studying water stress in plants and critical to water management planning for irrigation and dryland crops (Kern, 1995; Klocke and Hergert, 1990).

The concept of plant-available water capacity of soil was reviewed by Cassel and Nielsen (1986) and Kern (1995). Plant-available water-holding capacity of soil is estimated as the difference in water content between field capacity and permanent wilting point. Field capacity is the amount of water retained by a wetted soil after it has been freely drained by gravity for some period of time. The water-holding capacity of the soil is mostly dependent on soil porosity, which, in turn, depends on soil texture and structure. In Nebraska, soils vary from clay soils, with generally fine texture and high water-holding capacity, to sandy soils with coarse texture and low water-holding capacity. Sandy soils are most common in the Sand Hills region in north central Nebraska.

The soil root zone water-holding capacity, as a significant agricultural drought vulnerability factor, was used in this study to identify soils with different abilities to buffer crops during periods of deficient moisture. The data were obtained from the State Soil Geographic (STATSGO) database, U.S. Department of Agriculture – Natural Resources Conservation Service (Waltman *et al.*, 1997). In the original data, the root zone water-holding capacity was defined across an effective rooting depth, which is variable across the landscape. The depth varied according to root restricting zones in the soil profile, which can be due to bedrock, soluble salts, lithologic discontinuities, bulk density greater than 1.6 g/cc, water tables and other properties. This effective rooting depth used corn as the ideotypic crop. The rooting depth varies across the state. It is used to confine the water-holding capacity calculation. The maximum depth in the calculation is about 1.5 m, which is a limitation of the soils databases (Waltman, 1999).

The digital map of root zone available water-holding capacity for Nebraska was in GRASS GIS format with 200-meter spatial resolution and Albers Equal Area projection. For the GIS analysis in this study, the map was imported in ERDAS Imagine GIS (ERDAS Inc. Atlanta, GA). Considering the differences in soil water-holding capacity and its significance in crop buffering during drought, the original map was reclassified, using ERDAS Imagine, into four classes. The classes are designed to represent relative risk of crop failure during drought. The soils with water-holding capacity greater than 200 mm had the lowest risk, and soils with water holding capacity less than 100 mm had the greatest risk. Figure 4 shows the geographical pattern of soil water-holding capacity classes from a drought vulnerability perspective.

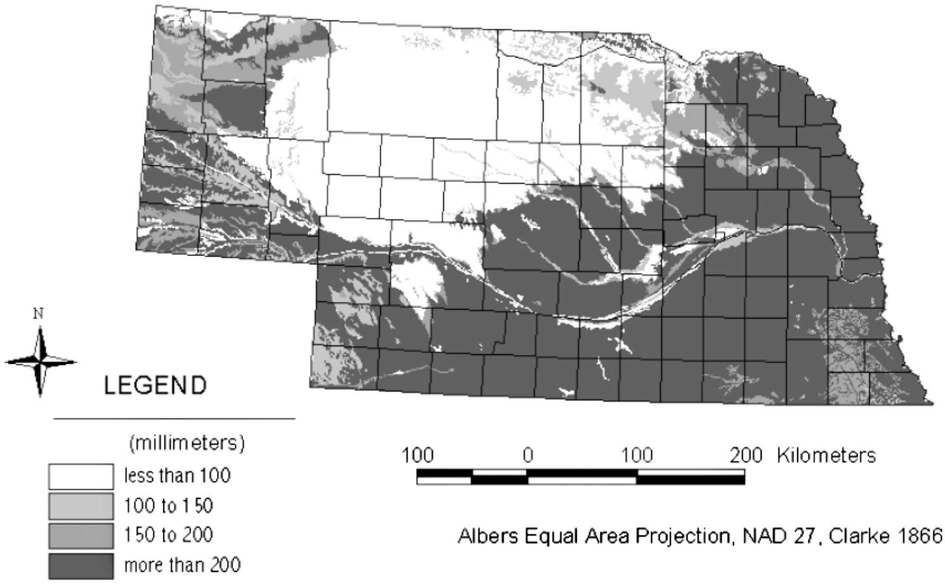

Figure 4. Soil root zone available water-holding capacity in Nebraska. Data source: STATSGO (USDA, NRCS, 1994). Spatial resolution = 200 meters.

3.1.3. Land Use

Land use is a one of the driving forces behind water demand and critical factors of agricultural drought vulnerability. Agriculture is the principle consumer of water worldwide. In Nebraska, a land-extensive agriculture is the primary transformer of the natural ecosystems: farms and ranches occupy 96 percent of the state's total land area. Water used per unit of land depends on the crop being grown and the agricultural/ irrigation technology and management used. The crops grown in the state vary according to the climatic gradients of precipitation and temperature. There is a strong tendency toward an increase in cropland with easterly direction. This is due to climatic gradients across the state described above and the distribution of soil texture and water holding capacity (Figure 4). Mainly due to availability of ground water and expansion of irrigation, croplands have shifted into climatologically marginal environments. Rangelands occupy nearly 9.3 million hectares and are located in the drier, predominantly semiarid, areas in the western portion of the state, largely corresponding with sandy soils.

The leading crops are corn, soybean, winter wheat, and sorghum. In 1996, Nebraska ranked third nationwide (after Iowa and Illinois) in corn production and second (after Texas) in cattle production (NASS, 1997). Nebraska has the second (after California) largest in the U.S. acreage of irrigated land (Irrigation Journal, 1999). In 1997, almost 40 percent of the cropland was irrigated.

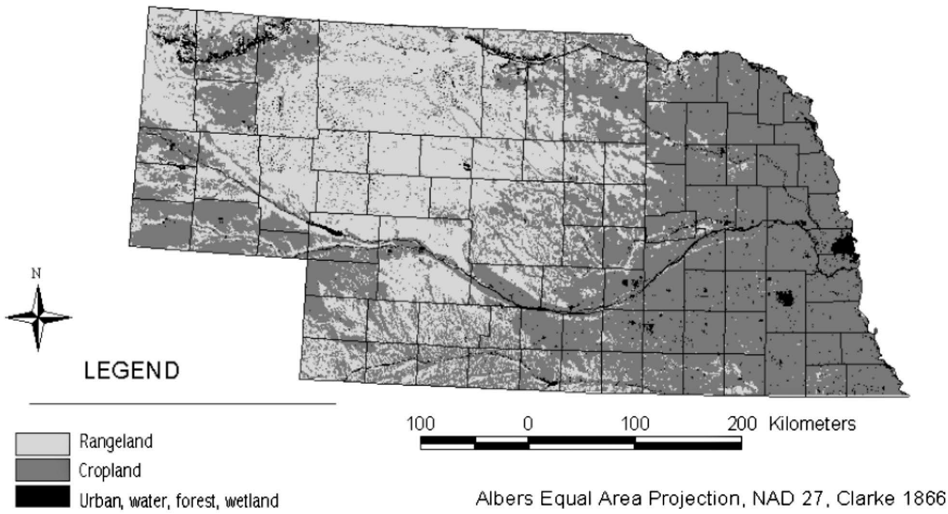

Figure 5. Land-use types of Nebraska. Data source: USGS 1:250,000 Land Use/Land Cover database. 200-meters spatial resolution.

The land use layer used in this study was edge matched and edited by the U.S. Environmental Protection Agency (Region VII) from USGS 1:250,000 Land Use/Land Cover database (Anderson Level II classification (Anderson *et al.*, 1976)). Dates of source data vary by region. The input map was reclassified into 3 classes for the drought vulnerability assessment, including cropland, rangeland, and non-agricultural land (e.g., forests, wetland, urban and bare land). Figure 5 gives the reclassified map of land use classes. The land use dataset does not separate irrigated and rainfed cropland. Identification of irrigated cropland was a part of this study.

3.1.4. Irrigation

In Nebraska, in 1997, 78,373 registered wells and about 5,000 surface water rights supplied water to about 3.2 million hectares of crop and pastureland (National Agricultural Statistic Service, 1998). Irrigation is very important for Nebraska farmers and for the State's economy. It increases economic returns, stabilizes net income, and reduces production risk. Each irrigated acre increases net farm sales by $125 and gross state product by $250. Irrigation is worth $250 million to Nebraska farmers; it increases Nebraska economic output by $2.1 billion and provides almost 2000 jobs (Supalla, 1997).

There is no consensus in the literature whether irrigation reduces or increases vulnerability to drought (Lockeretz, 1981; Opie, 1989; Jackson, 1991). During the long-term and/or severe droughts, farmers may have a higher cost of crop production because of increased water and energy cost for irrigation. In some cases, farms may temporarily lose water rights because of seniority and this could result in reduced crop yields. However, in most cases, and especially, during a short-term drought, irrigation farming provides more security for crop growers, especially in the central and western portions of the state, and reduces the societal vulnerability to drought impacts. In this study, the assumption that access to irrigation lessens vulnerability to agricultural drought was based on the fact, that irrigation farmers have a better drought mitigation measure relative to dryland farmers and an improved ability to cope with a short-term drought conditions.

The following technique was used to identify irrigated cropland. The mosaic of 18 Landsat Thematic Mapper (TM) satellite images (acquired during the 1991 through 1993 growing seasons) was created at the Center for Advanced Land Management Information Technologies (CALMIT) at the University of Nebraska–Lincoln; this mosaic was used as a base map for on-screen digitizing. The cell resolution of the image was 40 meters. The image was displayed in a color infrared ("false color") composite (bands combination 2, 3 and 4), which allowed better discrimination between types and conditions of vegetation. Two datasets, including surface water irrigation vector coverage, obtained from the Topologically Integrated Geographic Encoding and Referencing (TIGER) database (U.S. Census Bureau, 1999), and the 1996 vector coverage of registered irrigation wells (Nebraska Department of Water Resources, 1998), were used to approximate the irrigation sources on the satellite image of Nebraska. Vector coverages were overlaid with the image during on-screen digitizing. Boundaries of irrigated fields were digitized on the screen as polygon features using ArcView GIS.

Many of those fields in the proximity of the mapped registered irrigation wells were likely irrigated. Fields with center-pivot irrigation were most apparent on the image and simple to digitize, especially in western Nebraska, where the contrast between irrigated cropland and rainfed grassland was most evident. Fields may be irrigated fully, as a supplement to rainfall, or not at all in any given year, depending on local weather conditions and on individual farming practices. However, for the purpose of the drought vulnerability assessment, the availability of the irrigation sources for a given field was considered a vulnerability-lessening factor. To define the boundaries of the fields irrigated by surface water, the coverage of surface water canals was compiled from the 1995 TIGER dataset. The feature classes representing "man-made channels to transport water" were extracted from the TIGER dataset for each county and then edge-matched to compile irrigation canal coverage for Nebraska. In addition, some areas in the proximity of the naturally flowing water features (i.e., streams and rivers) were also considered as irrigated.

For verification of the digitized areas, data on areas of irrigated crops in Nebraska counties for 1996 were obtained from the Nebraska Department of Agriculture's Agricultural Statistics Service (1997). The percent of irrigated land compared to total county land area was calculated for each county. The same procedure was done for the digitized irrigated areas in each county. The Nebraska coverage of irrigated land and the coverage of the county boundaries were intersected in ArcView to identify the exact area of irrigated fields within each county. Then, the percent of land under irrigation was calculated for each county.

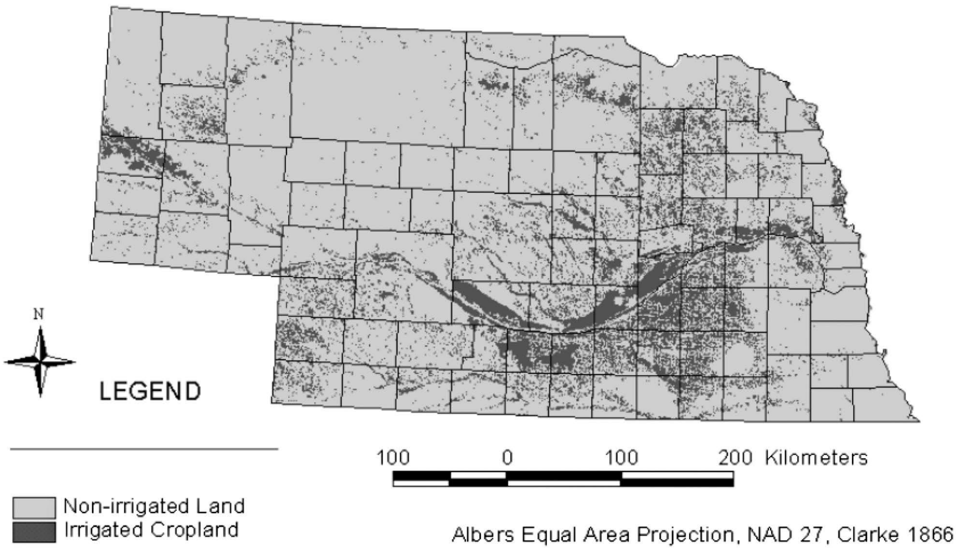

Figure 6. Irrigated cropland in Nebraska was digitized using mosaic of Landsat TM images of Nebraska (1993), irrigation canals data from U.S. Census Bureau 1999, and irrigation wells coverage from Nebraska Department of Water Resources (1996). Spatial resolution = 200 meters.

The results of this comparison showed that most of the digitized counties had from 0 to 8 percent difference in percentage of irrigated land from the agricultural statistics data. Overall, the differences in the irrigated land areas are largely attributed to two factors: (1) approximation of the irrigated acreage in the Agricultural Statistics dataset (the irrigated hectares are rounded up to the closest 202 or 402 hectares); (2) a digitizing error due to differences in time of Landsat Thematic Mapper acquisition (1991–1993), well coverage (1996) and irrigation canals data (1995). The resultant vector coverage was exported into ArcInfo GIS (ESRI, Redlands, CA) and converted to a grid at 200 meters spatial resolution. At the next step, the grid was exported into ERDAS Imagine image format at Albers Equal Area Projection, NAD 27, Spheroid Clarke 1866 (Figure 6).

3.2. Framework for Derivation of Drought Vulnerability Map

To produce an agricultural drought vulnerability map for Nebraska, probability of seasonal crop moisture deficiency (Figure 3), soil root zone available water-holding capacity (Figure 4), land use types (Figure 5), and irrigated cropland (Figure 6) maps were combined in ERDAS Imagine GIS to determine the areal extent of combinations of classes present. A numerical weighting scheme was used to assess the drought vulnerability potential of each factor. This approach was similar to those described in the "DRASTIC" methodology for groundwater pollution assessment (Aller *et al.*, 1987), the approaches for food security mapping that were summarized by Eastman *et al.* (1997) and drought proneness mapping by Thiruvengadachari and Gopalkrishna (1993).

The following numerical weighting scheme was used to assess drought vulnerability. Each class of four vulnerability factors has been assigned a relative weight between 1 and 5, with 1 being considered least significant in regard to drought vulnerability and 5 being considered most significant (Table 1). The choice of weights was based on an informed assumption on relative contribution of each factor to overall agricultural drought vulnerability. For example, rangeland and cropland were ranked 1 and 2, respectively, which shows that agricultural producers of these land use types may be vulnerable to drought and experience similar losses. However, rangeland was ranked slightly lower, due to better adaptability of rangeland vegetation to climatological fluctuations. Availability of irrigation support was ranked 1 and 4, which indicates a significant difference in the ability to withstand the lack of precipitation between dryland and irrigation farmers. "Dummy" weights of 20 and 100 have been assigned to the "non-agricultural land" class for masking purposes, since this class was not included in the agricultural drought vulnerability assessment, and to the "irrigated land" class in order to perform a separate analysis on irrigated areas. The final result of the combination of factors was a numeric value, which was calculated through the "union" mathematical function in ERDAS Imagine GIS by simple addition of the weights. For example, if a particular pixel/cell has a value of 4 on the probability of deficient moisture map, 3 on the root zone available water-holding capacity map, 1 on the land use map, and 4 on the irrigation map, then the composite value for that pixel becomes 4 + 1 + 3 + 4 = 12. All the GIS data layers were co-registered with their respective cell coordinates.

The output numeric values were analyzed in two steps: for rainfed land and for irrigated land. A high numeric value within each category was assumed to be indicative of a geographic area that is likely to be vulnerable to agricultural drought. The resulting map was reclassified into four classes, identifying geographic areas with "low" vulnerability, "low-to-moderate," "moderate," and "high" vulnerability (Figure 7). The derived classes of the final map were based on the numerical weights, informed judgment and the analysis of the combined input variables.

4. Results and Discussion

The "low" vulnerability class includes portions of two land-use types: irrigated cropland and rainfed rangeland. For the most part, this class follows the pattern of irrigated cropland in eastern and central Nebraska, with scattered patches in western Nebraska where soils have high water-holding capacity. Relatively small areas of rangeland, within this class, are located in central and southern Nebraska. A large portion of the land assigned to this class has a low or moderate probability of Seasonal Crop Moisture Deficiency (SCMD) and is un-

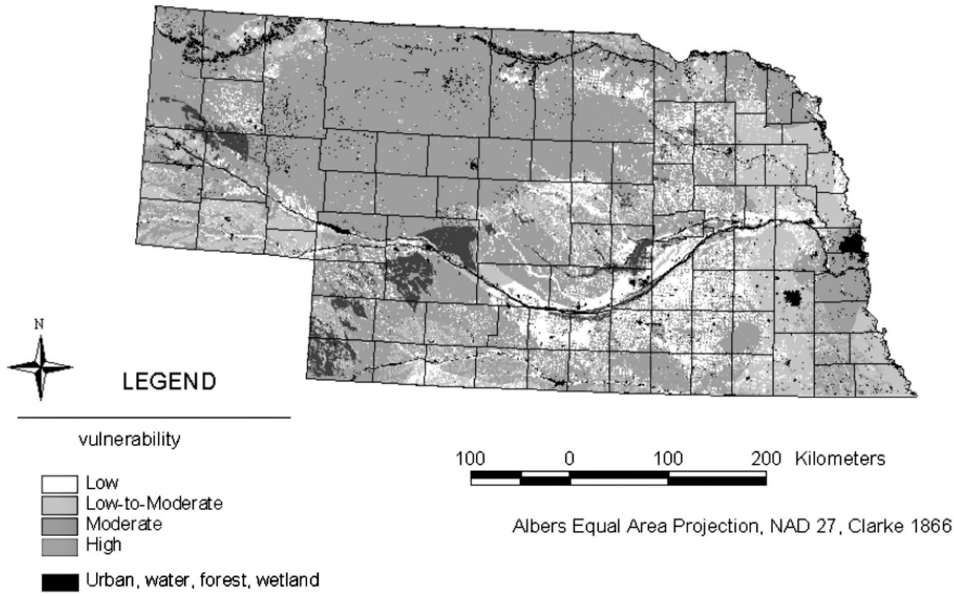

Figure 7. Agricultural drought vulnerability of Nebraska. Spatial resolution = 200 meters.

Table I. Weighting scheme for assessing agricultural drought vulnerability in Nebraska.

Agricultural drought vulnerability	Vulnerability class	Drought vulnerability factor class's score (weight)
Land use types	Rangeland	1
	Cropland	2
	Water, wetland, urban, forest	*20 (masking)*
Soil root zone available water holding capacity (mm)	More than 200	1
	150–200	2
	100–150	3
	Less than 100	4
Probability of seasonal crop moisture deficiency (%)	Less than 30 (low)	2
	30–50 (moderate)	3
	50–70 (high)	4
	More than 70 (very high)	5
Irrigation support	Available	*100 (masking)*
	Not available	4

derlain by soils with high Root Zone Available Water Holding Capacity (RZAWHC). The cropland and rangeland assigned to the "low" vulnerability class are vulnerable to agricultural drought; however, the vulnerability is lessened by the presence of irrigation, generally sufficient seasonal moisture and clay type soils, which provide a good buffer for crops during periods of deficient moisture. In the case of long-term drought, those areas may be affected by negative impacts of drought, but for the most part, the farmers are better prepared for drought and can withstand and recover faster from a drought event than dryland farmers can, for example.

The class of "low-to-moderate" vulnerability primarily consists of rainfed cropland and rangeland with RZAWHC greater than 150 mm and with low to moderate probability of SCMD. Small portions of irrigated cropland with either low probability of SCMD and sandy soils or with a combination of high probability of SCMD and high RZAWHC were also assigned to "low-to-moderate" vulnerability. The irrigated cropland of this class is mostly located in central and western Nebraska, while the rainfed cropland occupies a relatively large portion of eastern Nebraska. The rainfed cropland in this class represents a transition zone between low and moderate drought vulnerability, outlining the areas where the risk associated with dryland crop production is increased, but the large percentage of soybeans and sorghum in the crop acreage lessens the dryland farmers' vulnerability to drought. Where soils have high RZAWHC, soybeans have a better ability to recover after short periods of drought, and sorghum has better drought tolerance than corn.

Even though irrigation is considered a vulnerability lessening factor, combinations of sandy soils and high or very high probability of deficient moisture during the growing season places portions of irrigated cropland into the "low-to-moderate" vulnerability class. For example, the irrigated cropland along the North Platte River valley is assigned to this class because of very high (90 percent and higher) probability of deficient moisture for corn, which dominated (61 percent) the cropland. Under such conditions, irrigation of corn can become very expensive and the amount of water applied may not be sufficient for the crop, unless drought resistant varieties are planted.

The class of "moderate" vulnerability is the largest class in Nebraska. It combines various land-use types, soils, and SCMD probabilities, although in eastern Nebraska the boundaries of this class approximately follow the patterns of moderate probability of SCMD (Figure 3). This class also shows soils with lower RZAWHC. The rainfed cropland portion of this class is characterized by a high percentage of dryland corn. Eastern Nebraska often receives enough moisture for corn production. However, during drought events the crop can be significantly damaged and farmers' income may be reduced because of the absence of mitigation measures (such as irrigation, for example). Soils with lower RZAWHC in southeastern Nebraska also increase farmers' vulnerability to drought by not being able to provide a buffer for crops during periods of water shortage.

In southwestern Nebraska, counties have large acreages of corn for grain, which is mostly under irrigation. The combination of soils in that region with low RZAWHC (from 100 to 150 mm) and very high probability of SCMD can greatly affect the cost of irrigation and therefore place the region in the "moderate" vulnerability class. The increased cost of irrigation can influence farmers' decision not to irrigate to the full crop requirement.

The largest portion of the "moderate" vulnerability class is represented by rangelands, for the most part located in the Sand Hills region. Reece *et al.* (1991) indicated that in any given year, Nebraska's rangeland vegetation is either in recovery phase or under the direct influence of drought. Reed (1993) also emphasized the sensitivity of rangeland vegetation to moisture stress. Farmers and ranchers involved in hay and range livestock production in the region are vulnerable to impacts of drought. In the case of drought, the damage can be done not only to the water supply, but also to the livestock's winter forage supply, which can make ranchers even more vulnerable to the effects of subsequent hazard events.

Increases in the probability of SCMD and decreases in soil RZAWHC increase the regional vulnerability of crop and livestock producers. In southwestern Nebraska, for example, rainfed cropland is assigned to the "high" vulnerability class because of the combination of soils, climatology, and cropping patterns. However, most of the farmers adjust to such conditions using various soil conservation techniques, tillage practices, and crop rotations. Data on geographic distribution of such practices are not available on a statewide basis, hence they were not included in this study. However, in the future, research incorporating such data in vulnerability assessment can provide more accurate representation of regional vulnerabilities. As for rangeland, the areas of "high" vulnerability, for example, are shown near the western Platte River valley. High and very high probability of SCMD in combination with sandy soils with low RZAWHC may significantly affect hay production and forage for livestock. With proper drought management, such as keeping appropriate stocking rates and storing above-average levels of forage for livestock during years when rainfall is sufficient (Reece *et al.*, 1991), vulnerability can be lessened.

The resulting agricultural drought vulnerability map is at best only as accurate as the least accurately digitized base map. Inaccuracies arise from digitizing, during vector to raster conversion of the datasets to 200-meter grid cell resolution, and projection conversions of the imagery and data layers.

5. Conclusions

A map of agricultural drought vulnerability was intended as a first assessment of drought vulnerabilities in Nebraska. The map of agricultural drought vulnerability synthesized a variety of data and serves as an indicator of areas deserving a detailed drought vulnerability and risk evaluation. The key factors of agricultural drought vulnerability in Nebraska, available for this assessment, included probability of seasonal crop moisture deficiency, soil root zone available water-holding capacity, land-use types, and irrigation. A numerical weighting scheme was used to assess drought vulnerability potential for the classes within each factor. The weights were assigned according to the level of influence of each class on agricultural drought vulnerability. The output map contained four classes of vulnerability: "low," "low-to-moderate," "moderate," and "high."

The authors recognize that limitations in acquisition and representation of spatial data did not allow inclusion of all biophysical and, especially, social factors of vulnerability in this assessment. Social data, mostly available through U.S. Census Bureau and National Agricultural Statistic Service, would limit the analysis to various administrative boundaries and are often outdated. However, in the future drought vulnerability research inclusion of socio-economic data such as diversity of local economies and sources of income may be considered. Another social factor, which can be used as a vulnerability lessening criteria, is the percent of farms acquiring crop insurance, or the percent of acreage insured under crop insurance. Crop insurance is a mitigation measure that compensates losses due to drought impacts, and as such plays a major role as a management tool. In drought vulnerability assessment, a variable such as ratio of drought insurance policies to the number of farms can help determine level of drought mitigation in a county. At the present time, available data on insurance policies from the Risk Management Agency, U.S. Department of Agriculture contain all policies combined and do not distinguish between drought and other perils.

It is also clear that more research needs to be done in developing weighting schemes of vulnerability factors. Nevertheless, despite these limitations, the method presented in this paper can be a step forward in developing techniques for drought vulnerability assessments and in reducing the impacts associated with drought in the state. Identifying regional vulnerabilities can lead to adjustment in agricultural practices and the selection of more appropriate cropping patterns in order to get maximum yields during normal precipitation years and lessen crop yield declines and income loss during drought years. The map of drought vulnerability can help decision makers visualize the hazard and communicate the concept of vulnerability to agricultural producers, natural resource managers and others. Education of Nebraska decision makers about agricultural drought vulnerability should be the next step. Since Nebraska is climatically diverse, ranging from Udic to Aridic soil moisture regimes, this study can have broad spatial extrapolation to the Great Plains and the eastern Corn Belt region.

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