Assessing and Addressing Cross-Scale Environmental Risks: Information and Decision Systems for the Management of the High Plains Aquifer

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Global Environmental Assessment Project
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The Global Environmental Assessment (GEA) project is a collaborative team study of global environmental assessment as a link between science and policy. The Team is based at Harvard University. The project has two principal objectives. The first is to develop a more realistic and synoptic model of the actual relationships among science, assessment, and management in social responses to global change, and to use that model to understand, critique, and improve current practice of assessment as a bridge between science and policy making. The second is to elucidate a strategy of adaptive assessment and policy for global environmental problems, along with the methods and institutions to implement such a strategy in the real world.

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Publication abstracts of the GEA Project can be found on the GEA Web Page at http://environment.harvard.edu/gea. Further information on the Global Environmental Assessment project can be obtained from the Project Associate Director, Nancy Dickson, Belfer Center for Science and International Affairs, Kennedy School of Government, Harvard University, 79 JFK Street, Cambridge, MA 02138, telephone (617) 496-9469, telefax (617) 495-8963, Email nancy_dickson@harvard.edu.

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FOREWORD

This paper was written as part of the Global Environmental Assessment Project, a collaborative, interdisciplinary effort to explore how assessment activities can better link scientific understanding with effective action on issues arising in the context of global environmental change. The Project seeks to understand the special problems, challenges and opportunities that arise in efforts to develop common scientific assessments that are relevant and credible across multiple national circumstances and political cultures. It takes a long-term perspective focused on the interactions of science, assessment and management over periods of a decade or more, rather than concentrating on specific studies or negotiating sessions. Global environmental change is viewed broadly to include not only climate and other atmospheric issues, but also transboundary movements of organisms and chemical toxins.

The Project seeks to achieve progress towards three goals: deepening the critical understanding of the relationships among research, assessment and management in the global environmental arena; enhancing the communication among scholars and practitioners of global environmental assessments; and illuminating the contemporary choices facing the designers of global environmental assessments. It pursues these goals through a three-pronged strategy of competitively awarded fellowships that bring advanced doctoral and post-doctoral students to Harvard; an interdisciplinary training and research program involving faculty and fellows; and annual meetings bringing together scholars and practitioners of assessment.

The core of the Project is its Research Fellows. Fellows spend the year working with one another and project faculty as a Research Group exploring histories, processes and effects of global environmental assessment. Academic year 1997-8 focused specifically on the past three decades of climate change, long-range transport and tropospheric air pollution assessment experience with special attention to Europe and North America. These papers look across a range of particular assessments to examine variation and changes in what has been assessed, explore assessment as a part of a broader pattern of communication, and focus on the dynamics of assessment. The contributions these papers provide has been fundamental to the development of the GEA venture. I look forward to seeing revised versions published in appropriate journals.

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ABSTRACT

Between 1940 and 1995, the High Plains aquifer, a major source of irrigation water underlying eight U.S. states in the semi-arid Great Plains, declined in some areas by as much as 50%. As an environmental and resource management challenge, depletion of the High Plains aquifer exemplifies a class of problems which are characterized by cross-scale interactions - those in which events or phenomena at one level of scale influence phenomena at other levels. Environmental problems of this nature have historically posed unique problems and pitfalls for management, particularly when scales of biogeophysical and human systems are mismatched, or when linkages across scales are ignored by decision makers. This research investigates what kinds of responses to a cross-scale problem - in this case, irrigation-induced depletion of the High Plains aquifer - result in effective management strategies, focusing on how information and decision making systems can be structured to support such management.

In this effort groundwater management regimes are compared in Kansas, Nebraska, and Texas using evidence from approximately 50 interviews at federal, state, and local levels. This study suggests that effective cross-scale management is associated with: 1) coordination of information systems across scale (e.g. when scale-dependent comparative advantages in information production and dissemination are exploited); 2) coordination/orchestration of decision making systems across scale (e.g., when decisions made at one level provide opportunities to, or at least do not constrain, decision makers at another level of scale); 3) integration of information and decision functions (e.g., decision makers working closely with information providers in an iterative and long term process of research agenda setting, model building, and model testing); and 4) addressing linked issues simultaneously (e.g., when one agency has responsibility for addressing numerous linked issues such as water quality and quantity and surface and groundwater.)
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<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ARS</td>
<td>Agricultural Research Service</td>
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<tr>
<td>CRP</td>
<td>Conservation Reserve Program</td>
</tr>
<tr>
<td>CSREES</td>
<td>Cooperative State Research, Education, and Extension Service</td>
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<tr>
<td>EDA</td>
<td>Economic Development Administration</td>
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<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
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<tr>
<td>ERS</td>
<td>Economic Research Service</td>
</tr>
<tr>
<td>NASS</td>
<td>National Agricultural Statistics Service</td>
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<tr>
<td>NRCS</td>
<td>Natural Resources Conservation Service</td>
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<tr>
<td>USDA</td>
<td>U.S. Department of Agriculture</td>
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<tr>
<td>USGS</td>
<td>U.S. Geological Survey</td>
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## Kansas

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<tr>
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<tr>
<td>DWR</td>
<td>Division of Water Resources</td>
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<tr>
<td>GMD</td>
<td>Groundwater Management District</td>
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<tr>
<td>GMD#3</td>
<td>Groundwater Management District #3</td>
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<tr>
<td>KGS</td>
<td>Kansas Geological Survey</td>
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<tr>
<td>KSU</td>
<td>Kansas State University</td>
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<tr>
<td>KWO</td>
<td>Kansas Water Office</td>
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<td>SCS</td>
<td>State Conservation Commission</td>
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## Nebraska

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<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ARD</td>
<td>Agricultural Research Division</td>
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<tr>
<td>CSD</td>
<td>Conservation and Survey Division of the University of Nebraska-Lincoln</td>
</tr>
<tr>
<td>DEQ</td>
<td>Department of Environmental Quality</td>
</tr>
<tr>
<td>DWR</td>
<td>Department of Water Resources</td>
</tr>
<tr>
<td>EPU</td>
<td>Extension Programming Unit</td>
</tr>
<tr>
<td>IANR</td>
<td>Institute of Agriculture and Natural Resources</td>
</tr>
<tr>
<td>NRC</td>
<td>Natural Resources Commission</td>
</tr>
<tr>
<td>NRD</td>
<td>Natural Resource District</td>
</tr>
<tr>
<td>UNL</td>
<td>University of Nebraska-Lincoln</td>
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<tr>
<td>URNRD</td>
<td>Upper Republican Natural Resource District</td>
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## Texas

<table>
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<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>HPUWCD</td>
<td>High Plains Underground Water Conservation District #1</td>
</tr>
<tr>
<td>TAMU</td>
<td>Texas A&amp;M University</td>
</tr>
<tr>
<td>TNRCC</td>
<td>Texas Natural Resource Conservation Commission</td>
</tr>
<tr>
<td>TTU</td>
<td>Texas Tech University, Lubbock</td>
</tr>
<tr>
<td>TWDB</td>
<td>Texas Water Development Board</td>
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<tr>
<td>UWCD</td>
<td>underground water conservation district</td>
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1. INTRODUCTION

Between 1940 and 1995, the High Plains aquifer, a major source of irrigation water underlying eight U.S. states in the semi-arid Great Plains, declined in some areas by as much as 50% (McGuire and Sharpe 1997). For a region in which irrigated agriculture is the economic foundation and supplies a significant portion of food and fiber products to U.S. and international markets, depletion of the aquifer has become a major focus of attention. Concern about the decline of the aquifer, and its resultant economic and social impacts, has gained the attention of decision makers and scientists at all levels of scale within the U.S., from the individual farmer to county officials to state agencies to federal politicians and agency administrators (Kromm and White 1992; McGuire and Sharpe 1997). Taking advantage of variance in management regimes in response to aquifer depletion, this research is a beginning step in exploring the characteristics which contribute to effective management of a cross-scale environmental risk, with special focus on the structure and role of information/assessment and decision making systems.

As an environmental and resource management challenge, depletion of the High Plains aquifer exemplifies a class of problems which are characterized by cross-scale interactions - *those in which events or phenomena at one level of scale influence phenomena at other levels*. Environmental problems of this nature have historically posed unique problems and pitfalls for management. For example, “[w]hen human responsibility does not match the spatial, temporal, or functional scale of natural phenomena, unsustainable use of resources is likely, and it will persist until the mismatch of scales is cured.” p. 561, (Lee 1993). The importance of the pitfall of mismatched scales and ignorance of linkages between scales becomes heightened as we realize two issues. First, different systems - biological, chemical, physical and human - function and interact at different temporal and spatial scales (Rosswall, Woodmansee et al. 1988; Holling 1995; Kincaid 1996; Gunderson, Holling et al. 1995). Second, extraordinary complexities of interaction result, and there is abundant opportunity for disjunction across systems (Holling 1995). Both the scientific and policy arenas have addressed a range of cross-scale environmental problems including transboundary water and air pollution, fisheries management, and a host of global environmental risks such as climate change, biodiversity loss, acid rain, and ozone depletion.

Despite the emergence of these kinds of issues on both assessment and policy agendas, there has been relatively little systematic examination of how the cross-scale dynamics of a problem influence both assessment and decision systems and their interaction (Young 1995; Gibson, Ostrom et al. 1997; Cash and Moser 1998; Wilbanks and Kates 1998). Thus, this research investigates what kinds of responses to a cross-scale problem - in this case, irrigation-induced depletion of the High Plains aquifer - result in effective management strategies, focusing on how information and decision making systems can be structured to support such management. In this effort, the research addresses the following questions:

1) What are the national to local linkages in information production and transfer, and decision-making?
2) What institutions and processes exist which encourage or discourage the cross-scale transfer of “useful” information to users, and the transfer of users’ needs to assessors?

3) What institutions and processes exist which lead to effective cross-scale decision making?

4) Under what conditions do these institutions operate and under what conditions are they effective?

5) How can information/decision-making systems be improved to effectively address the problems associated with cross-scale environmental risks?

These questions probe an understanding of the boundaries which define scale. Essentially, this study investigates what can effectively bridge boundaries imposed by the scalar nature of human and natural systems. I undertake this research with the understanding that scale-related boundaries are only one class of many kinds of boundaries which characterize environmental problems. For example, boundaries between disciplines, between interests, between institutions, and between academic research and applied research, all provide challenges to environmental decision making. This multiplicity of boundaries raises important questions which are beyond the scope of this research, but nonetheless important: Are the mechanisms for bridging these boundaries similar? Which boundaries provide the greatest challenges or obstacles? For which kind of problems?

While the main thrust of this research is to understand what kinds of information and decision systems give rise to effective management of the aquifer, a parallel goal is to apply the lessons from the history of High Plains management to other, incipient, cross-scale environmental problems - in particular to climate change. Like depletion of the aquifer, climate change is characterized by: causes, impacts, mitigation and adaptation responses which cross different levels of scale; long time horizons; common pool resource attributes; extreme climatic events; uncertain variability in the natural system; large scale environmental changes due to aggregate small-scale human actions; and multiple linkages to other natural resource and environmental issues (Glantz 1988). In addition, in the U.S., beginning efforts are underway to create a national climate change assessment process, one goal of which is to incorporate regional and local perspectives while providing useful input to subnational decision making. It is understood, of course, that climate change differs from aquifer depletion in significant ways, including its global scale, importance of international dynamics, and vastly larger linkages to other issues and sectors. Despite these differences, however, to begin to address a problem as unprecedented and complex as climate change, it seems plausible to turn to communities and institutions which have a 50+ year history of managing a natural resource which shares a number of critical attributes with climate change and other global environmental problems.

2. THEORIES OF SCALE AND CROSS-SCALE DYNAMICS

Scientists often characterize natural phenomena in terms of scale. Ecologists, for example, delineate biomes, forests, stands, patches, trees, branches, leaves, components of leaves, etc. As a conceptual construct the notion of scale has been helpful in gaining understanding of biogeophysical events and relationships. Implicit in this notion of scale, is the existence of
boundaries that separate scales. In biogeophysical systems these boundaries are blurred and micro to macro changes in scale can be described as continuous. Human societies have also evolved and structured themselves around different scales and delineated, often sharp boundaries between these levels. In modern American society, these are organized, for example, by the social and political units: individual, family, community, city, county, state, and nation. It is this context of a problem defined by multiple scales within which I investigate what contributes to effective management.

While the factors which lead to management effectiveness have long histories of investigation and analysis, how the cross-scale dynamics of environmental problems matter in the management process has been relatively understudied (Gunderson, Holling et al. 1995; Gibson, Ostrom et al. 1997; Cash and Moser 1998). When scale has been addressed, it has been in isolated disciplines, primarily in the natural sciences and geography, and little attention has focused on the dynamics of cross-scale interactions. Moreover, despite the importance of recent research on the role of communication and information in the response to environmental risks, little effort has been made to understand how the assessment of scientific and technical information which is gathered, constructed, and produced at one scale interacts with decision making and risk management strategies at other levels of scale. In addition, there is little understanding of how policies and decisions at one scale constrain or provide opportunities at other scales. Rarely has there been an attempt to synthesize concepts from existing fields into an understanding of how to integrate information and decision systems across different levels of scale in order to more effectively support environmental management.

Despite these limitations, however, we can turn to a number of disciplines which provide some grounding in these issues. Hierarchy theory, and its reliance on theories of complex systems from ecology, highlight the synergistic effects which characterize multi-scale dynamics and provide insights into how events at one scale control or constrain events at other scales (Gunderson, Holling et al. 1995; Holling 1995; Levin 1997). Human geography has a long history of treating human phenomena as scale-related, and focuses on connections across spatial and temporal scales (Cash and Moser 1998). Recent theories of adaptive management by Holling, Walters, and others (also rooted in ecology), explicitly identify scale as a crucial factor in the management of complex issues, and demonstrate the importance of assessment processes which lead to cross-scale transfers of scientific information (Holling 1978; Walters 1986; Lee 1993; Gunderson, Holling et al. 1995). Current examination of institutions which manage common pool resources has provided insights into how the “nested” nature of human systems can provide constraints or opportunities on management communities, and that institutions at different levels of scale may have comparative advantages in information and/or decision making capabilities (Ostrom 1990; Bromley 1992; Ostrom, Gardner et al. 1994). Finally, explorations of environmental federalism, provide key insights into understanding the conditions under which decision making authority should reside at different levels of scale, with a special focus on issues of externalities, commons and public good problems (Esty 1996; Kincaid 1996; Revesz 1997).

Though the theoretical perspectives outlined above are from disparate fields, a reading of these literatures leads to several general propositions. Management institutions and processes can be effectively supported by information and decision systems which: coordinate decision making across different scales; coordinate information systems across different scales;
integrate decision making and information functions across different scales; and exploit comparative advantages in information and decision making capabilities at different scales (Cash and Moser 1998). This paper begins to explore the validity of these propositions.

3. METHODOLOGY

3.1 Dependent variable

The dependent variable of this study is the effectiveness of management systems in addressing multi-scale environmental risks. The ultimate indicator of effectiveness of a natural resource management system is arguably the state of the resource itself. At least two problems are associated with using this as a measure in the case of aquifer management. The first is the practical difficulty of measuring the state of the resource and ascribing causal relationships between management actions and the resource. The second problem is based on the heterogeneity of the management goals. For example, while there is broad agreement throughout the region on the necessity to conserve the underground water resource, localities and states have different preferences for depletion rates of the aquifer itself. Thus, for example, using water levels of the aquifer, rates of depletion or similar physical measures of the aquifer would not be appropriate. (Future iterations of this research will identify state of the resource measures, as well as indicators of behavioral change - see Section 7.2.)

Given these limitations, it is therefore necessary to look “upstream” in the causal chain to identify indicators of effectiveness. One such example is the existence of management actions aimed at changing the behavior of a target group - in this case irrigators and other groundwater users. The existence of the implementation of management actions, from educational activities to rules which regulate use of groundwater provides one type of indicator of effectiveness of management agencies. For example, everything else being equal, it can be argued that a management regime which has regulations concerning the quantity of water that can be pumped from wells within its jurisdiction is more effective than a management regime which has no such requirement. A catalog of management actions found in the study area is listed in Table 1.

In addition to this outcome measure, a variety of process indicators of the effectiveness of information and decision systems can also be employed. While identifying measures of “effectiveness” of processes has consistently proven difficult in the social sciences, recent work in the arena of global environmental policy has proposed several qualities of environmental regimes that characterize effective systems. For example, effectiveness of institutions for dealing with global environmental issues can be characterized in terms of the level of concern expressed by political actors, improvements in the credibility of the contractual relations among participating parties, and the capacity of relevant institutions to carry out their tasks. the impact on the resource (Haas, Keohane et al. 1994; Connolly 1996).

Using these concepts as starting points, I identify two other process-based indicators of effectiveness which are more applicable to the national through local scales upon which this research is focused. The first is the conducive management environment. This refers to a
legal and political environment in which rule making is possible, and the threat of enforcement of rules is credible. The second is the information capacity. Information capacity is an indicator of how well a management regime facilitates the transfer of scientific and technical information to the potential users of that information. In the context of water management in the High Plains region, this includes such aspects as the accessibility of state-of-the-art irrigation practices for farmers, or the availability of models which forecast water levels of the aquifer for managers.

Understanding that no single measure can appropriately capture “effectiveness”, I used this suite of three indicators to gauge effectiveness: 1) management environment; 2) information capacity; and 3) management actions. It should be noted that this categorization of different indicators is an analytic tool and should not be taken to mean that there are not links between these four indicators. In fact, there are causal relationships between all three of these indicators. Part of the goal of this research is to try to understand causal pathways through which these different indicators act and contribute to effective management.

3.2 Explanatory variables

Based on a review of both the theoretical and practical literatures and preliminary interviews in the High Plains region, I identified several potential explanatory variables. The most important of these explanatory variables investigated in this study as possible determinants of effectiveness are the degree to which:

1) information systems are coordinated across scales
2) decision systems are coordinated across scale
3) decision and information systems are integrated
4) linkages between different resource issues are addressed

Information systems which are coordinated across scales refers to arrangements in which the process of information research, production, and packaging is orchestrated across different levels of scale. One component of this might be that comparative advantages in the information process that are scale-related are utilized. For example, large scale federal agencies such as the US Geologic Survey (USGS) have the technical resources and data to produce complex hydrogeologic models of the entire aquifer. Local groundwater management districts might be well-suited to collect local water use and well water-level data. An example of an information system which is well coordinated across scales is one in which the USGS and a local groundwater district collaborate to provide local-scale inputs into regional-scale models, which can in turn provide locally relevant forecasting. In addition, another component of a well coordinated information system is that is supports two-way communication between the producers and users of information. This process provides information to decision makers, such as farmers, but also facilitates the communication of information needs from the decision-maker to the researcher or producer of information.

Decision systems which are coordinated across scales refers to arrangements in which a deliberate process of decision making involves decision makers from all affected levels of scale. The intent of such coordination is to ensure that decision making at one level of scale does not unwittingly constrain decision making at other levels of scale. An example of cross-scale
coordinated decision making would be a state water agency whose planning process requires input from and authorizes veto power to local water authorities.

*Decision and information systems which are integrated across scales* refers to institutional arrangements in which the decision making process and the information production process are intimately tied together. This notion runs counter to traditional notions of scientific information being produced outside the policy process and then later funneled (i.e. “disseminated”) into the policy process. An example of integrated decision and information systems would be managers in a planning agency working closely with engineers and hydrological modelers to create forecasting models that include specific regulatory parameters that can be used by the managers to make regulatory decisions.

*Linkages between different resource issues being addressed* refers to a more holistic approach to management in which the connections between one issue (e.g. groundwater quantity) and other issues (e.g. surface water quantity) are addressed simultaneously - either within the same organization or through close collaboration between organizations (Weinberg and Kling 1996).

### 3.3 Geographic focus

As discussed above, the geographic focus of this study is the High Plains aquifer in the U.S. Great Plains (see *Figure 1*). One primary reason for studying this region is that it allows for a comparative analysis within the region of the determinants of effective information and decision systems. For example, within the High Plains region there is variance in both natural resources (e.g., precipitation, temperature, soil type, storm frequency, aquifer saturated thickness and recharge rates) and, more important, variance in institutional and political structures which address climate and water-related issues (e.g., state laws, state-specific land-grant college systems, the existence or type of natural resource management districts, the allocation of decision making responsibility to different actors at different levels of scale, etc.). Within the region, however, there is relatively little variance in overall socio-economic, industrial, and cultural makeup.

In this first phase of the study, one county in each of Kansas, Nebraska, and Texas was chosen as a field site. (see *Figure 2*) The three states were chosen because: 1) they overly 75% of the aquifer (McGuire and Sharpe 1997); 2) they account for 89% of the irrigated acreage overlying the aquifer (Kromm and White 1992); 3) within each of the three states, the heterogeneity of the aquifer is represented, so variance of the natural resource itself can be controlled for; 4) agricultural production and irrigation development have taken similar paths in the three states, and thus a range of economic factors can be controlled for; and 5) there is useful institutional variance in water resource information and decision making - for example, all three states have evolved three different ways of managing the aquifer at the state and local levels; and all three states have different relationships with federal agencies such as the USDA and USGS. The three counties (Finney County in Kansas, Chase County in Nebraska, and Lamb County in Texas) were chosen for this phase of the research because the level of risk of depletion, measured by saturated thickness, depth to thickness and historical rates of decline, faced by each is
relatively similar, and thus controlled for. In addition, the three counties are all within local, multi-county management districts, but the structure and function of these districts are different (see Figure 3). Thus, for this phase of the research, variables such as the characteristics of the aquifer, risk of water depletion, general economic characteristics, and presence of a local management body are held relatively constant, while specific institutional and management variables vary.

### 3.4 Policy focus

The primary focus of this research is on an area of decision making that has been historically concerned with water availability and climate variability: the agriculture sector. Agriculture in the U.S. is an excellent case in which to study the issues outlined in the introduction because: 1) agriculture is fundamentally influenced by local and regional water availability and ultimately large-scale climatic processes; 2) there is a long history of agricultural decision making and information utilization which cuts across scale - as exemplified by the USDA/Cooperative State Research, Education, and Extension Service (CSREES) and the land grant system which is designed to provide bridges between national-regional-state-county-household level decision makers and researchers; and 3) a wide variety of public and private sources of information in the agricultural sector allow for an analysis of what kinds of sources of information are effective under what kind of conditions.

### 3.5 Data collection

Two sources of evidence have been used in this investigation. The primary source of evidence is that based on structured interviews completed in the three states and through telephone interviews in Washington D.C. using a consistent interview protocol (Moser and Cash 1998). In particular, the interviews established what types of information decision makers need, which sources they turn to, why certain sources are preferred to others, what were the characteristics of the decision making process, and what individuals or organizations were collaborators, and which posed obstacles. Interviewees in each state and at the federal level were selected through an iterative process from a number of sources: from the pertinent literature; through U.S.-wide and state-specific searches for non-governmental, governmental, academic and non-academic organizations involved in agricultural and water resource issues; and finally, once the interviews were underway, through recommendations from interviewees themselves. Interviews were conducted with county and area extension and Natural Resource Conservation Service agents, research scientists, private industry managers, state and local planners, representatives of non-governmental organizations, and elected officials on local resource management boards (see Appendix for a list of interviewees). The second source of data complements the first and is comprised of documentary evidence gleaned from assessments, reports, legislative documents, mission statements, newsletters, and fact sheets.
4. THE HIGH PLAINS AQUIFER AND AGRICULTURE

4.1 The physical resource

Derived from stream-borne sediments which originated in the Rocky Mountains, the High Plains aquifer is a subsurface geologic formation laid down 3.8 million years ago. The aquifer underlies an area of 174,000 square miles (for comparison, the area of New England is 67,000 square miles) (McGuire and Sharpe 1997). Consisting of a layer of unconsolidated clay, silt, gravel, and sand, the formation is saturated with water and can be several hundred feet thick. In the context of utilizing and managing the resource, several key characteristics of the aquifer are important to understand. “Saturated thickness” is a measure of how thick the saturated layer is. This varies greatly throughout the aquifer and is one important factor in determining the amount of water available for irrigation (see Figure 4). In addition to variance in saturated thickness, flow rates within the aquifer vary as well. In general, however, flow rates are relatively slow (in the regard, the aquifer is less analogous to an underground lake or river, than to a sponge) (Buchanan and Buddemeir 1993). This relatively slow and heterogeneous transfer of water means that the aquifer is not a pure common pool resource - depletion in one part of the resource might have no effect on other parts of the resource. This, however is scale-dependent, and at lower levels (100m-10k) this common pool resource characteristic is prominent. The depth to the aquifer (“depth to water”) varies as well, and ranges from being at the surface (in some stream beds), to over 200 feet deep. The greater the depth to water, the greater the initial (well-digging) and operating (energy for pumping) costs are for irrigation (Kromm and White 1992; Buchanan and Buddemeir 1993).

A wide range of factors influence the rate of recharge, or replenishment, of the aquifer including precipitation, soil type, vegetation, permeability of the substrate, irrigation return-flow, and seepage from streams, canals, lakes, and reservoirs. Within the aquifer, recharge rates range from .25 inches per year to 6 inches per year (McGuire and Sharpe 1997). This relatively slow recharge rate combined with pumping rates of as much as 30 inches per year, has resulted in utilization of High Plains aquifer water being referred to as mining. In many places in the region, the resource is essentially non-renewable (Green 1992).

4.2 Development of the aquifer for agriculture

Irrigated agriculture is particularly well suited to the High Plains region. It is a semi-arid region with extremely variable precipitation, yet abundant and fertile soil with moderately long growing season. In addition, the geologic nature of the aquifer results in especially good quality water, as the substrate acts as a purifying filter (Buchanan and Buddemeir 1993). The climatic variability and semi-arid nature of the area led to pumping for irrigation in the late 1880’s as early farmers attempted to secure a predictable source of water. Despite some advances in pumping and energy technology in the 1890's and early 1900's, the great increase in development of the aquifer did not begin until the 1930’s when the dust-bowl drought and New Deal-era government programs provided incentives for farmers to exploit the groundwater (Green 1992).
Further technological advances in drilling, pumping, and delivery, and the advent of inexpensive energy, favorable financing, government subsidies and crop prices all contributed to steady increases in irrigated acreage from WWII to the present (see Figure 5).

Currently, approximately 95% of water withdrawn from the aquifer is used for agricultural purposes. (McGuire and Sharpe 1997). Irrigated cropland accounts for 37% of the harvested cropland in the High Plains region, and for specific crops such as corn, 50% of the harvested cropland is attributed to irrigated acres (Kromm and White 1992). From a national perspective, the region produces significant shares of the U.S. output of corn, wheat, sorghum, cotton, and cattle (fed on irrigated feed). In addition, 20% of the irrigated land and 30% of the irrigated groundwater in the U.S. is in the High Plains region. Clearly, “[i]rrigated agriculture sustains the High Plains and is central to an integrated agribusiness economy….” (Kromm and White 1992).

4.3 Depletion of the aquifer

With relatively low natural recharge rates and the dramatic increase in the use of groundwater throughout the region, declining water levels were noticed in parts of the region as early as the 1940’s and 1950’s (McGuire and Sharpe 1997). By the 1970’s, farmers and officials at all levels of government were expressing a need to more closely examine the issue of aquifer depletion. In the mid-1970’s the U.S. Congress authorized two assessments. The first was a national effort, the Regional Aquifer-System Analysis, which examined the hydrogeology of all the major aquifers in the U.S. The second assessment process brought together federal, state, local government agencies with private consultants within the High Plains region to analyze the potential economic and social impacts of aquifer depletion and management options (High Plains Associates 1982; Weeks, Gutentag et al. 1988; Kromm and White 1992). This assessment was done in parallel with hydrogeological studies conducted by the U.S. Geologic Survey (USGS). Motivation for these studies at the national level centered on national food security issues. The local and state concerns focused on potential negative local and state economic and demographic impacts of partial or total depletion of the aquifer. At the time, increased pumping costs, due to both the increasing depth to water and the energy price shocks of the mid and late 1970’s, as well as the potential social disruption due to the abandonment of irrigated farming in the region placed concern for the aquifer high on the public’s agenda.

One of the central issues that also focused state and local attention during this time was the common pool resource attributes of the aquifer. While pumping water in Nebraska will have no impact on water levels in Texas, at smaller levels of scale (farms, counties, and immediately across jurisdictional lines), exploitation of the resource at one point decreases water availability at other points. In addition, current research, management and legal concerns are focusing on the relationship between ground and surface water, particularly how depletion of the aquifer affects down-stream surface water levels.

By the mid-1980’s, both the USGS and states within the region had undertaken individual and collaborative ongoing monitoring, analysis, and modeling efforts to assist in the management of the resource (McGuire and Sharpe 1997). The most recent analyses of the aquifer, for example concludes:
The large volume of water withdrawn from the aquifer for irrigation purposes since 1940 has had a substantial effect on water levels in the aquifer...Water-level changes in the High Plains aquifer, however, have not been uniform. Large regional differences in rates of ground-water recharge and withdrawals for irrigation as a result of regional variability in climate, soil, land use, and historical development of irrigated agriculture have substantially affected the geographical patterns of water-level change in the High Plains aquifer. (McGuire and Sharpe 1997, sheet 1).

This heterogeneity can be seen in Figure 6 in which portions of southwest Kansas, southwest Nebraska, and northern Texas have experienced significant declines from 1980 to 1995. (The study sites for this phase of the research have been chosen in these “higher risk” areas.) Despite extreme declines in some areas (up to two hundred foot declines, or 50% of the saturated thickness), large portions of the region have experienced no significant decline. In fact, some areas of the aquifer have experienced significant increases in the water level, most notably in the southern section of the aquifer in Texas, and in eastern Nebraska. These increases are due primarily to abnormally high precipitation between 1980-1995 and seepage from surface water diversions (McGuire and Sharpe 1997).

Given the national food security considerations, social and economic concerns and the common pool characteristics of the resource, depletion of the aquifer is currently still identified as a major problem in all of the states overlying the aquifer as well as in the federal government. Throughout the region, conservation to slow or reverse depletion is a management goal.

4.4 Studies of water management on the High Plains

As concern about the aquifer has risen on the public and policy agendas, research on the developing management regimes has followed. Kromm, White and their colleagues at Kansas State University have undertaken an extensive two-decade investigation of agricultural decision making in the High Plains, particularly at the level of the farmer. Principally through detailed surveys, this investigation documents the preferences of irrigators for local (multi-county management district) control of a variety of management actions, and for preferences for state responsibility of enforcement of water law and coordination of research (Kromm and White 1984; White and Kromm 1995). The research also identifies sources of information which are associated with high levels of adoption of water conservation technologies by farmers - private agricultural consulting firms, university research stations and trade magazines (Kromm and White 1991). In addition, specific management districts have been recognized as leaders in the region in providing effective management and conservation guidance, primarily through education and technical assistance programs (Roberts 1992).

Specific case studies of individual areas within the High Plains region have provided additional insights to complement the comparative research described above. A description of the Upper Republican Natural Resource District (an area covered in my study) in Nebraska exposes a model of management that combines elements of state-level control, local control and privatization (such as allowing the selling of water rights, and water banking) (Stephenson 1996).
An historical account of irrigation in northwest Kansas traces the development of local groundwater management districts (GMDs) and highlights tensions between maintaining individual autonomy and vesting authority in local GMDs (Buchanan 1992). In Texas, a survey-based study explored irrigators’ perception of the role of the local management district, the High Plains Underground Water Conservation District No. 1 (also an area covered in my study), finding that, in general, stakeholders find the district to be responsive to their goals and values and supporting Kromm and White’s findings of preference for local, if any, control (Brook 1997).

These studies provide rich analyses of farmer-level decision making and preferences, insights into the functioning of local management districts, and the identification of effective management regimes throughout the region. I hope that the study presented in this paper will contribute to this literature by adding a comparative and systematic analysis of the determinants of management effectiveness with specific attention to how information and decision systems contribute to addressing this cross-scale problem.

5. DESCRIPTIVE RESULTS: INFORMATION AND DECISION SYSTEMS IN THE HIGH PLAINS

5.1. Federal groundwater regulatory policy

The federal government has no direct jurisdiction or regulatory authority over management of groundwater quantity in the High Plains. (It does, however, have jurisdiction over underground water quality, through the Clean Water Act of 1972 and 1987, which is administered by the Environmental Protection Agency (EPA). It is uncertain how federal management of water quality will influence state and local management of water quantity.) Indirectly, however, two types of federal legislation have influenced underground water management. First, by providing subsidies for corn, a water intensive crop, the 1985 Farm Bill created incentives for farmers in the High Plains to switch from lower water crops such as wheat. The 1996 Farm Bill, however, establishes a timetable for eliminating these subsidies, provides a variety of cost-share and education programs, and extends the Conservation Reserve Program (CRP), a subsidy and management program which provides incentives to farmers to take certain types of land out of production. All of these programs are designed to induce water conservation. Implementation of these aspects of the Farm Bill is overseen by the Natural Resources Conservation Service (NRCS) within the U.S. Department of Agriculture (USDA).

Second, the federal tax code also indirectly contributes to individual water management decisions. The groundwater depletion allowance permits irrigators to write off land value depreciation that results from depletion of the aquifer, thus providing disincentive for water conservation practices (White and Kromm 1995).
5.2. Federal Information systems

While the federal government has little direct regulatory influence on aquifer management, several agencies provide scientific and technical information with regards to agriculture and water management at the national, state and local levels. The agency with the longest history of such involvement is the USDA and its agricultural research and extension functions, established in the 1860’s with the initiation of the land-grant college system. (Extension is the process of disseminating applied research information to a target user, in this case, the farmer.) Recently, the Cooperative State Research Service and the Cooperative Extension Service were consolidated to form the Cooperative State Research, Education, and Extension Service (CSREES).

The CSREES mission emphasizes partnerships with the public and private sectors to maximize the effectiveness of limited resources. CSREES programs increase and provide access to scientific knowledge; strengthen the capabilities of land-grant and other institutions in research, extension and higher education; increase access to and use of improved communication and network systems; and promote informed decision making by producers, families, communities, and other customers. (CSREES Mission Statement, (U.S. Department of Agriculture 1997)

The CSREES has created partnerships in each of the 50 states, primarily through the land-grant colleges. The detailed structure of these partnerships (and the relationship between research and extension) differs from state to state, but the general organization of the system includes: national offices in Washington D.C. and Maryland; a research/education/extension center housed in the state’s land-grant college (e.g., at Kansas State University (KSU)); area research and extension offices throughout the state (e.g., The KSU system divides Kansas into 5 such areas); and one extension office in each county; and an elected advisory board in each county.

As noted above, the NRCS (previously named the Soil Conservation Service, and instituted in the 1930’s under the title, Soil Erosion Service), like the CSREES, is structured to provide information to local farmers on conservation practices. It also has a national to local structure: a national office; regional offices (e.g., the Northern Plains Region includes Colorado, Kansas, Montana, Nebraska, N. Dakota, S. Dakota, and Wyoming); state offices (not associated with the land-grant college); area offices (e.g., Kansas is divided into 6 such areas); county offices; and a locally elected (by county) soil and water conservation district board of directors (the authority of this board differs from state to state.) In addition to providing information, the NRCS administers cost-share programs, and acts as a regulatory body with regards to the CRP and highly erodible lands, regulating practices on farms who participate in the CRP.

With their infrastructures designed to allow two-way flows of information, both the CSREES and NRCS set national research, education, extension, and conservation agendas with input from local and state stakeholders. In this regard, the NRCS is less flexible than the CSREES since its actions are more closely tied to specific provisions of congressional legislation (e.g. CRP mandates).

In addition to the NRCS and CSREES, the USDA has several other research divisions with varying impact at state and local levels. These include the Agricultural Research Service (ARS),
the Economic Research Service (ERS), and the National Agricultural Statistics Service (NASS), all of which provide data and analysis to national, state, and local clients. In varying degrees, all five of these USDA agencies collaborate.

The U.S. Geological Survey (USGS) within the Department of Interior is another federal agency which plays an important role in providing decision-makers with information about the aquifer. Through national, regional, and state offices, the USGS has been the lead scientific organization in studying, characterizing, analyzing and mapping the hydrogeologic features of the aquifer. As with the other federal agencies described above, the relationship of the USGS to state and local agencies varies.

Through Congressional authorization in the late 1970’s, the Department of Commerce’s Economic Development Administration (EDA) carried out an assessment of the potential impacts of depletion of the High Plains aquifer and possible alternative options in dealing with the decline. Collaborating with six state agencies, U.S. Army Corps of Engineers and private consulting firms, the EDA published its final report in 1982. Since that time, the Department of Commerce has had little direct involvement with aquifer depletion issues.

5.3. Kansas

5.3.1. State-level activity

It is hereby recognized that a need exists for the creation of special districts for the proper management of the groundwater resources of the state; for the conservation of groundwater resources; for the prevention of economic deterioration; for associated endeavors within the state of Kansas through the stabilization of agriculture; and to secure for Kansas the benefit of its fertile soils and favorable location with respect to national and world markets (Kansas Statute 82a-1020-1040 1972).

Thus begins the Groundwater District Management Act of 1972 in which the Kansas state legislature provided the means by which locally initiated and organized Groundwater Management Districts (GMD), in concert with the Chief Engineer in the state’s Department of Agriculture’s Division of Water Resources (DWR), gained authority to manage many aspects of the High Plains aquifer. Through a locally elected board of directors, GMDs have the authority to acquire land, construct and operate water projects, provide research, education, and technical services, levy water use charges, require water meters, adopt “reasonable standards and policies relating to the conservation and management of groundwater”, propose rules and regulations (which must be accepted by the Chief Engineer), recommend to DWR the designation of an intensive groundwater use control area (which then allows DWR to regulate pumping more strictly in that area), and submit an annual management plan to DWR for approval.

All activities of the GMD must be consistent with existing water law based on the 1945 Water Appropriations Act. Four main tenets of the law are prior appropriation (i.e., “first in time, first in right”), a requirement of beneficial use, a “use-it-or-lose-it” provision, and state
ownership of the underground water resources (Smith 1989). While GMDs have a range of
authority, the ultimate arbiter of underground water rights is the Chief Engineer. Enforcement of
rules and regulations promulgated by the GMD is also the responsibility of the Chief Engineer.
New wells require permits that are processed and accepted by both the GMD and DWR, which
ultimately has the authority to allocate quantity limits. DWR has area offices throughout the
state which act as liaisons between the GMDs and the DWR office in Topeka. There are
currently 5 GMDs in Kansas (see Figure 7).

In addition to the DWR, the state’s separate water planning office, the Kansas Water Office
(KWO), is responsible for developing a comprehensive multi-year State Water Plan. The process
for developing this plan emphasizes public participation and relies heavily on input from GMDs,
DWR, and other federal, state, and local agencies such as Basin Advisory Councils (BAC) -
twelve elected councils set up by river basin throughout the state which have responsibility for
managing surface water. The State Water Plan is used to advise the governor and legislature on
policies relating to water use and water conservation. KWO, also allocates funds from a State
Water Fund to water management and conservation projects throughout the state. In addition,
KWO works closely with the State Conservation Commission (SCS), another agency which
allocates funds for a variety of water conservation efforts. In collaboration with DWR, KWO has
also made recent attempts to address the challenges posed by ground and surface water
interactions. For example, GMDs and BACs have different boundaries, partially overlapping
jurisdictions, and potentially competing interests. Current efforts are underway to reconcile those
differences and establish a management system which accounts for the relationship between
ground and surface water, and between linked environmental issues, such as depletion of the
aquifer and degradation of water quality.

In order to acquire scientific information that is used in the policy process, these various state
planning, policy, and regulatory agencies turn to three primary sources: internal technical staff
(or the internal technical staff of other state agencies - for example DWR might consult with a
hydrologists from KWO); the Kansas Geological Survey (KGS); and the state USGS office in
Lawrence. KGS is an academic and applied wing of the University of Kansas (thus it is not
directly associated with Kansas State University or its research/extension functions), whose
charge is to provide geological and hydrological information to public and private clients
throughout the state. KGS works closely with state agencies such as DWR, KWO, and SCS and
with local agencies such as GMDs in designing research projects to assess groundwater resource
problems. It helps maintain a statewide database of the aquifer that is used and updated by all of
the previously mentioned agencies. Within KGS, the research
agenda is set by a combination of the interests of scientists on staff, but more important through
the needs of their clients, who supply them with a large portion of their funding through
contracted assessment projects.

The USGS office in Lawrence has historically provided well monitoring, stream gauging,
mapping, and modeling expertise to the same clients that KGS serves. It has a rigorous scientific
review process and is noted for its unbiased research. Recently, the state office of USGS has
reduced some of its contracting for two reasons. First, given its rigorous scientific review
process, its turn-around time is often to slow for decision makers. Second, like other federal
agencies it is experiencing budget cuts, and thus is forced to charge increasing fees for
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contractual work. However, particularly for interstate court cases on water rights (Kansas is suing Nebraska for overappropriating water from the Republican River - the case hinges on the ground and surface water interactions), the USGS is seen as a particularly good source for unbiased information. Like the KGS, its research agenda is often set by its clients, though for the USGS, there is also direction from regional and national offices.

Finally, as the state’s land-grant college and CSREES center, KSU is the nexus for agricultural research and extension in the state. At its main campus, 5 area offices and 12 satellite research experiment stations throughout the state, it undertakes basic and applied research in such areas as irrigation technologies, irrigated cropping processes, and groundwater management strategies. Research at the main campus is well-coordinated with satellite facilities. More important, Kansas has become one of the few states to have fully integrated the research and extension arms of their program, providing opportunities for collaboration between the researchers and extension agents.

5.3.2. Groundwater Management District #3 and Finney County, Kansas

Groundwater Management District #3 was formed in 1976 to address the problem of local depletion of the aquifer. Run by an elected board from the twelve counties it covers, the district employs a full time professional manager and a technical, educational and administrative staff. It provides a variety of monitoring, education, and regulatory functions (see below for a more complete description).

The KSU Research and Extension Office in Finney County provides a variety of services in the county including education seminars, newsletter reports, radio and TV announcements, and walk-in and phone troubleshooting. It works closely with the KSU Southwest Research-Extension Center (the area research station) in planning demonstrations of efficient technologies, new cropping practices, and a variety of water management strategies based on applied research completed at the research station and elsewhere throughout the state and region. Both the county extension office and area research station have locally elected boards of advisors who help direct their workplans and set research agendas.

As with research and extension, NRCS has both county and area offices which serve the counties within GMD#3. While the majority of these offices’ time is spent administering provisions of the CRP and other aspects of the 1996 Farm Bill, they also engage in education about water conservation, and are the gatekeepers for cost-share funding that farmers can use to upgrade or install water efficient technologies. Each NRCS county office is directed by a locally elected Soil and Water Conservation District, which sets priorities for the cost-share program and other conservation activities.

The area office of DWR acts as liaison between GMD#3 and the state DWR office in Topeka. It helps with the well permitting process, and is the first line in the state water rights bureaucracy when disputes arise in the counties within its area. It also helps coordinate water monitoring data collection that is funneled to the state DWR office and KGS.
Private firms also play a role in groundwater management in the area. Irrigation supply companies provide farmers with a variety of water conservation-related equipment and technologies. They also collaborate with GMD#3 and KSU in producing educational activities, and with NRCS in designing water conservation programs, particularly as part of the cost-share programs. Agricultural consultants are individuals or firms who provide regular (once per week during the growing season) on-the-ground monitoring of farmers’ fields and advise their clients on irrigation management, among other things. Their sources of information include private input providers (seed, fertilizer, and irrigation companies), and the KSU research and extension system.

5.3.3. Local groundwater management - How the system works

To conceptually organize an understanding of how the management system works, the following section is organized by the explanatory variables described in Section 3.2.

To what degree are information systems coordinated across scales?

The information system from Finney County to the federal agency level is well coordinated. Two mechanisms exemplify this coordination. First, knowledge about cropping techniques, irrigation technology, and other on-farm information and the information needs of farmers are communicated well between GMD#3, and KSU research and extension at the county, area, and state levels. There are many institutionalized avenues in the system through which both the information and information needs are communicated between users and producers of information. The following structures facilitate this two-way communication: the close collaboration between GMD#3 and all levels of the KSU research and extension program, private firms, and the NRCS in providing educational activities; the recent merging of both state and federal level research and extension activities; the various elected boards (e.g. GMD#3, Soil and Water Conservation Board, and county extension advisory board) which advise NRCS and research and extension on what areas of research and outreach are important to pursue; and the county through national structure of the CSREES and NRCS.

Second, GMD#3 has often taken advantage of the technical and scientific expertise of USGS and KGS to get information for management decisions and model potential changes in the aquifer. The district has worked, in an ongoing capacity, with KGS to complete a range of assessments and model projected changes in the aquifer over the next 30 years, given specific kinds of management regimes which the district is exploring. In constructing their models, KGS obtained data from USGS and DWR. In turn, USGS, DWR, KGS depend on the well monitoring data collected by GMD#3 to update its database and baseline models of the aquifer.

To what degree are decision systems coordinated across scales?

In some respects, the decision making environment is one that is very conducive to cross-scale coordination. GMD#3 communicates on a regular basis with the area and state Division of Water Resources offices and the Kansas Water Office. Institutionalized structures are in place which requires coordination in such areas as management planning, permitting, and the development of rules. This institutionalized structure and open lines of communications ensures
that in most instances state and local decision making is complementary, and does not act at cross-purposes with one another. State legislative action (such as the Groundwater Management District Act) has, for the most part, created opportunities, empowered, and provided support for local management that also fits in to the larger context of the state’s interest in groundwater management. One area that is still hindered by poor coordination is enforcement. Under state law, DWR is responsible for the enforcement of regulations instituted by GMD#3, but currently does not have an aggressive enforcement program. For example, the Chief Engineer has authority to require a landowner to stop pumping, an action that has not taken place in GMD#3 despite the reporting of overpumping violations. This lack of coordination results in a situation in which the rules promulgated by GMD#3 have the potential of being viewed as not having the backing of the state, and state’s commitment to enforce the rules is questioned. As a result, GMD#3 is constrained in its decision making by the decision at the state level to not enforce local rules.

To what degree are the decision and information systems integrated?

Particularly at the level of scale of the GMD, the information and decision making systems are well integrated. The GMD is a decision making body and an education body, and it fully integrates information gathering and analysis into the decision making process. The example cited above of working with the KGS to develop an ongoing process of assessing the state of the aquifer and forecasting the future exemplifies this integration. In this regard, it is difficult to say where the assessment process stops and the decision making process begins. Elements of this are also seen at the state level in which planning agencies, staffed with hydrogeologists, work closely with agencies like KGS and USGS in a dynamic and iterative process of data collection, modeling, and policy making.

To what degree are multiple issues linked in the management system?

Historically, GMDs have been structured to address groundwater quantity issues. Surface water and groundwater quality issues, for example, have been addressed through different statutes and different state agencies. The conflicting jurisdictions, boundaries, and interests of the BACs and GMDs exemplifies this compartmentalization of issues. As noted before, the GMDs and BACs have just started working together, under the leadership of DWR and KWO to create more comprehensive water planning. In addition, GMD#3 is currently struggling with how to address water quality issues and is in the midst of determining its relationship with the State Department of Health and Environment, the regulatory body responsible for groundwater pollution prevention.

5.3.4. Local groundwater management - Is it effective?

This section outlines an analysis of the three indicators outlined in Section 3.1, resulting in a qualitative assessment of the effectiveness of GMD#3 in managing underground water.

Management environment

To some degree, GMD#3 is embedded in a management environment which is conducive to making decisions and creating rules and regulations. Backed by state laws and overseeing agency regulations, the district receives state support for its activities. This is particularly important
with regards to statutes which have vested the authority for some aspects of management in locally elected officials. The result is a system which has both local political credibility and support from the state level. In addition, the ability to coordinate from the local to state level allows for complementarity of action and the avoidance of conflicting state and local activities. However, the management environment is not conducive for either the state or local agencies to make credible commitments to enforce regulations such as pumping limits, or water waste bans.

**Information capacity**

The information systems work extremely well at facilitating the transfer of scientific and technical information between the potential users of that information. Overlapping networks of researchers, providers, education efforts result in a rich and dynamic system which is responsive to the needs of irrigators and water managers. An important role in this system is that of the information translator - a person or organization which acts as the bridge between research and action. Whereas, historically, farmers have relied on the public research and extension system as their primary source of information, farmers (and managers in GMD#3) are becoming increasingly reliant on private sources of information - provided by agricultural consultants or input firms. Thus, it is the consultants who are taking on the role of information translator or broker, between the state research facilities or input providers and the farmer.

**Management actions**

While GMD#3 and DWR undertake a wide range of activities the most important are: its educational role - teaching its constituents about the benefits of conservation and the availability of conservation technologies; having well spacing requirements; allocating pumping limits that are set by the state on a one time basis (at the time of permitting for a new well); moratoria on new wells in certain areas of the district that are already overallocated; establishing special control areas; banning waste of water; and participating in cost-share programs for water efficient technologies (see Table 2).

5.4. Nebraska

5.4.1. State-level activity

Nebraska water law was largely determined in an ad hoc basis by the courts, with little legislative input prior to 1972 (Smith 1989). These court decisions have established the state ownership of groundwater resource, the requirement of beneficial use, a “use-it-or-lose-it” provision, and the rule of correlative rights, in which one landowner may not use the resource such that other landowners’ rights are infringed upon, and that in times of scarcity, each landowner is entitled to a reasonable proportion of the underground resource (Smith 1989).

Since 1972, several fundamental legislative actions have shaped underground water management in the state. In 1972, Natural Resource Districts (NRDs) were created,
consolidating 154 single-purpose districts such as soil conservation districts, watershed boards, and water conservation districts into 24 multi-purpose governmental bodies. The boundaries of the districts approximately correspond with major rivers (see Figure 8). Governed by a board of locally elected directors, NRDs have broad powers of taxation, research, education, regulation, and enforcement, and are responsible for soil, water, wildlife, habitat, forest, and range management and conservation (Nebraska Natural Resources Commission 1986; Smith 1989). While there is significant local control of resource management, the NRDs are required to work in concert with other state regulatory and scientific agencies, including: the Department of Water Resources (DWR), which oversees the regulation of surface and groundwater (with a greater emphasis on surface water, leaving most groundwater regulation to the NRDs); the Natural Resources Commission (NRC), which coordinates resource management and planning throughout the state, produces annual state water plans, administers the distribution of conservation funds, and maintains a resource databank; the Department of Environmental Quality (DEQ), which implements federal and state pollution control programs, including dealing with underground water contamination; and the Conservation and Survey Division (CSD) of the University of Nebraska-Lincoln (UNL), which is, in essence, the state geological survey, providing technical and scientific research on the geology and hydrology of the state (Nebraska Natural Resources Commission 1986).

Responding to heightening concern about depletion of the aquifer, the legislature passed a series groundwater management and protection bills in the mid-1970’s to mid-1980’s. In addition to existing state requirements on well registration and well spacing (administered by DWR), these bills added new powers to the NRDs, enabling them to apply to DWR to designate special “control areas” where aquifer depletion was deemed especially serious, and, with final approval required by DWR, set more strict water conservation measures than would otherwise be allowable. They also required NRDs to submit water quality and quantity management plans, to DWR for approval. In cases where NRDs do not adopt controls, DWR has the authority to step in and regulate the water resources (Nebraska Natural Resources Commission 1986; Smith 1989).

Though these state laws supported some degree of management that integrated the treatment of surface and groundwater, and quality and quantity issues, legislation codified this integration in a an “integrated water management” and “conjunctive use” bill in 1996 which authorizes NRDs to establish “management areas” taking the place of the old “control areas”. These management areas are more comprehensive than control areas, dealing not only with depletion of groundwater, but with groundwater-surface water interactions and water quality issues as well. Again, the designation and administration of management areas is primarily the responsibility of NRDs, but requires the collaboration of DWR, DEQ, and NRC (Nebraska Department of Water Resources 1996).

As noted above, CSD is the organization responsible for conducting research, monitoring, and providing scientific and technical information to other state and local agencies on water resource issues. As a division within the University of Nebraska, it is housed within the Institute of Agriculture and Natural Resources. Funding derives from the university budget as well as through contracted projects with state agencies and NRDs, thus its research agenda is set by a
combination of internal and external initiatives. CSD also collaborates with federal agencies such as the NRCS and USGS on soil and water surveys.

As in Kansas, the Nebraska office of the USGS provides monitoring, modeling and mapping expertise to clients within the state, including CSD, DWR, NRC, and NRDs. The USGS office in Lincoln also houses the High Plains Aquifer Project, which coordinates data collection, analysis and mapping of the High Plains aquifer in the USGS offices in the eight states overlying the aquifer.

Both the extension service and agricultural research components of the CSREES are housed in the Institute of Agriculture and Natural Resources (IANR) at UNL, the Nebraska land-grant college, though are administered separately. The extension service is structured with faculty at the main campus, at 23 multi-county Extension Program Unit (EPU) sites, and in an extension office in every county in the state. Agricultural research, particularly that relating to irrigation technologies and water/crop management is run through the Agricultural Research Division (ARD) within IANR, and at eight research/extension stations throughout the state.

In addition to these government agencies, several multi-national input providers have state offices in Nebraska. Cargill, Monsanto and Pioneer Hi-Bred are all multinational seed production companies with research and development offices in the state, as well as a network or field and sales managers who work throughout the state, and in other states in the region. Valmont Industries, headquartered in eastern Nebraska, is one of the world’s largest manufacturers of irrigation equipment. It also distributes its products and its management information throughout the High Plains region

5.4.2. Upper Republican Natural Resource District and Chase County, Nebraska

The locus of responsibility for groundwater management in Chase County resides in the Upper Republican Natural Resource District (URNRD). Like all NRDs in the state, URNRD has broad regulatory, research, monitoring, and outreach authority, and integrates its management of groundwater quantity with its management of surface water, water quality, soils, wildlife and habitat conservation. URNRD is governed by an elected board of 11 directors from the three counties which make up the district, and has a staff of a manager, technicians and educators.

The UNL extension office in Chase County provides outreach to farmers through seminars, workshops, newspaper, radio, TV, and brochures. It works closely with the Southwest Four EPU (comprised of Dundy, Chase, Hayes, and Hitchcock Counties) office in coordinating programs and educational events. It also collaborates with the ARD West Central Research and Extension Center located in North Platte, 100 miles northwest of the Chase County seat of Imperial. Activities in the county extension office are guided by an elected advisory board which sets planning priorities and allocates county funds.

As in Kansas, NRCS serves the URNRD directly through both county and area offices. It also allocates most of its resources to CRP administration and other mandates from the 1996
Farm Bill, administers several cost-share programs for irrigation technology, and participates in a variety of educational activities. As in Kansas, each NRCS county office is directed by a locally elected Soil and Water Conservation District, which sets priorities for the cost-share program and other conservation activities.

Agricultural consulting firms, and seed, fertilizer, and irrigation equipment providers all serve the farmers in Chase County. They are also contributors to and beneficiaries of the URN RD/UNL/NRCS education and outreach programs.

5.4.3. Local groundwater management - How the system works

To what degree are information systems coordinated across scales?

Information systems about groundwater management in Chase County are well coordinated from the local to the federal levels. Institutions have been structured and relationships have developed over time to create a system in which two-way communication between users and producers of information is the norm. Elected advisory boards provide local NRCS and extension offices with information needs, and the system of local, area, state, and federal connections facilitates the communication of these needs to the appropriate researcher at the appropriate level. Information also flows in the opposite direction ultimately getting to producers. For example, URN RD works closely with county and area UNL extension offices and collaborates with the area research experiment station on ensuring the provision of timely up-to-date applied research results to farmers. Workshops are often co-sponsored by the district and extension and research offices, as well as by the NRCS county and area offices. A range of information is transferred through these activities, including about applied irrigation and cropping research, new technologies, incentive programs, and irrigation, fertilizer, pesticide, and seed products. Agricultural consultants and private input providers also act as an important link in this flow of information.

In terms of scientific information that is most useful to managers, the URN RD has ongoing relationships with CSD and USGS and contracts with both of these agencies to take advantage of their regional scale modeling capability to produce assessments and forecasts for different management scenarios. Collaborative efforts at data collection with URN RD, CSD, DWR, and DEQ allow for models which can predict both water quantity and water quality outcomes, and integrate groundwater and surface water management parameters. The production of “assessments” in this regard, are not defined by reports. In fact, while written reports are completed, it is the ongoing collaborative process of model building, testing, and data collection which characterizes the “assessment”.

To what degree are decision systems coordinated across scales?

Legislative actions with regards to groundwater have deliberately supported coordination from the NRD level to the state level. The NRC effectively serves in its role as facilitator between the many different state and local agencies which address water issues, and the relationship between URN RD, DWR, DEQ, and NRC is cooperative. Despite the tangle of agencies responsible for water management, the system is structured such that the planning
process is well-coordinated, and it is uncommon that regulatory decisions made at one level constrain decision making at other levels. For example, state statute and agency regulations have supported enforcement efforts by URNRD. In addition, the state courts, including the Nebraska Supreme Court, have upheld the regulatory and enforcement powers of URNRD in a number of test cases.

To what degree are the decision and information systems integrated?

The assessment and decision making process are highly coupled in URNRD. The managers of the district are intimately involved with both data collection/modeling of the aquifer and the planning and policy processes. URNRD utilizes CSD and USGS such that there are closely linked efforts of assessing problems, designing and implementing policy, and then evaluating outcomes. Similar integration is seen at the state level where CSD and USGS work closely, in an iterative fashion, with state planning and regulatory agencies and their own technical staff.

To what degree are multiple issues linked in the management system?

One of the hallmarks of the NRD system in Nebraska is the multi-purpose nature of the districts. The wide ranging authorities vested in the URNRD combined with good cooperation between states agencies such as DWR, DEQ, and NRC, and a state legislature which has legally recognized the connections between different management problems results in a system in which multiple issues are addressed in an integrated fashion.

5.4.4. Local groundwater management - Is it effective?

Management environment

The legal and political institutions which make up the groundwater management system in Chase County create a management environment which supports rule making backed by credible enforcement. The existence of locally elected and empowered directors collaborating with active, transparent and well coordinated state agencies, all in a framework of a legislature and judiciary which is consistent, produces a system which is both locally politically legitimate yet still responsive to state interests. This balance between local and state interests is also exemplified by state ownership of the resource with delegation of management authority at the local level, in the context of the ever-present threat of state control. The system has proven to be flexible in the face of a changing environment and evolving science. As new issues and concerns have arisen on the agendas at federal, state, and local levels, the NRD has been able to adapt its management strategies to respond to new problems.

Information capacity

The information infrastructure which connects farmers and water managers in Chase County to scientists, researchers, planners in state and federal agencies effectively facilitates the transfer of information in both directions. This infrastructure is characterized by networks of research centers, extension agents, agricultural consultants, and input salespeople embedded in a system of collaborating local, state and federal agencies. As in Kansas, a key player in this network is that of the information translator, the bridge between a producer and user of information. This role is
increasingly being filled by private consultants who provide connections between input providers, the extension and research community, and farmers.

**Management actions**

Within Nebraska, URNRD has a reputation for being an active manager of the groundwater resource. This is evidenced by the wide array of both educational and regulatory functions that their district undertakes. A comprehensive list of these is offered in Table 2, but the most significant include: setting a 15 inch per year pumping cap (this rate can vary from year-to-year depending on the state of aquifer); required chemical application permits; having well spacing requirements; requiring metering and reporting water usage; instituting a moratorium on the building of new wells in certain parts of the districts; privatizing the resource to some degree by allowing “banking” and water “pooling” (see Table 1 for a brief description), and actively enforcing regulations. In addition to these regulatory functions, URNRD also engages in a wide range of educational activities as well as cost-share programs to provide incentive for the use of efficient irrigation technologies.

5.5. Texas

5.5.1. State-level activity

Groundwater management in Texas has largely been framed by the absolute ownership doctrine. This doctrine stipulates that landowners have full rights to underground water pumped from their property. In addition, there is no correlative rights associated with groundwater - rights to underground water on one property are *not* diminished even if pumping that water results in decreased groundwater availability on a neighbor’s property. A strict interpretation of the absolute ownership doctrine has been supported in a variety of court cases which have been brought before the Texas Supreme Court from 1904 to the present (Smith 1989).

Despite the absolute ownership doctrine, active groundwater management by state and local authorities has a long history in the state, partly due to the fact that depletion of the aquifer was observed relatively early. In 1949, the legislature enacted statutes which allowed the creation of voluntary locally controlled underground water conservation districts (UWCDs) in which counties, or parts thereof, can vote to form or join a UWCD. The UWCDs were empowered to raise revenue, conduct research, provide education, and regulate well spacing and production in limited ways. Legislation in 1985 further expanded the role of UWCDs while also giving the state authority to require a UWCD to be formed. Activities of the UWCDs, however, can not abrogate landowners’ absolute right to groundwater. There are currently nine UWCDs in the High Plains region ranging in size from less than a county to 15 counties. (see Figure 9)

In 1957 the Texas Water Development Board (TWDB) was created as the state agency charged with three primary duties: provide state-wide surface and ground water supply planning; to conduct hydrogeological research and modeling and to maintain a statewide water resources
database; and provide grants and loans for a variety of different water and conservation projects. A recent statute has expanded the scope of the TWDB, authorizing it to facilitate regional scale and integrated quantity/quality water planning in collaboration with local and state planning and management institutions (Texas Senate Bill 1 1997). Though not a regulatory agency, it induces management planning and conservation through its funding. Areas that are not part of a UWCD or which do not have a TWBD-approved water management plan are not eligible for grants or loans dispensed by the agency. Although it has offices only in Austin, TWDB officials travel throughout the state on a regular basis to meet with local officials.

The Texas Natural Resource Conservation Commission (TNRCC) is the state environmental protection agency. As such, it has regulatory functions and implements both federal and state air and water quality mandates. It is the principal regulatory agency responsible for addressing groundwater contamination and collaborates with TWBD, UWDCs and U.S. EPA. It also works in concert with the Texas Department of Agriculture whose responsibility is to regulate pesticide and herbicide use in accordance with state and federal laws.

The state CSREES partners are housed at Texas A&M University (TAMU) in College Station. As in Nebraska, the extension service and agricultural research components are separate. Though administered through Texas A&M’s main campus, there are 14 area extension offices throughout the state and 250 county extension offices, which are guided by local boards of elected directors. The Texas Agricultural Experiment Station also has area offices throughout the state, which, for the most part are combined with the extension offices. The Texas Water Resource Institute, focusing on research, training, and technology transfer, is a special unit within the Agricultural Experiment Station, and was created by the federal 1984 Water Resources Research Act of 1964). The extension and research divisions collaborate extensively in producing a range of research and educational activities on irrigation, cropping and water management. In fact, some of the earliest work on efficient irrigation sprinkler systems were originated in the TAMU system.

Other universities within Texas also perform research, development, and outreach functions with regards to underground water management. The most prominent of these is Texas Tech University (TTU) in Lubbock. The Water Resources Center within the Department of Civil Engineering at TTU has played an active role in both modeling efforts and policy development for High Plains aquifer management.

USGS has a state office in Texas, as well as satellite offices throughout the state, though none are in the High Plains region. USGS has collaborated with TWDB in its data collection and modeling efforts, but has not been active with local or regional efforts in the High Plains.

As in both Kansas and Nebraska, the NRCS has state, area, and county offices which provide the same functions that they do throughout the plains: implementation of the CRP; collaborative educational programs with state and local agencies (including UWCDs); and cost-share programs to provide incentives for adopting water efficient irrigation technologies.
5.5.2. High Plains Underground Water Conservation District #1 and Lamb County, Texas

The High Plains Underground Water Conservation District #1 (HPUWCD) was formed in 1951 and is the largest and most active of the UWCDs. As for all UWCDs, Lamb County, and each of the other member counties, has had to elect to be a part of the district through a popular referendum. The district is governed by a board of directors elected from the county which sets policy, sets research agendas, and hires a full time staff of a manager, technicians, scientists, educators and administrators. It is funded through property taxes and is empowered to set limited regulations (well spacing and the banning of tailwater - wasted water which runs off a field), to complete research and to provide education.

Lamb County farmers routinely use a wide range of educational and informational material from the county and area extension programs as well as from the experiment station located in Amarillo and the researchers at TTU. Extension agents and research scientists collaborate with one another, as well as with staff from HPUWCD and NRCS.

As with other states in the region, NRCS plays an active role, not only in education, but in cost-share programs and CRP administration that assists farmers in adopting and maintaining water efficient technologies and conservation practices.

Private firms also play an important role in information dissemination in Lamb County. Agricultural consultants and input provider firms are key links between R&D and application of new technologies and practices in the field. As agricultural consulting has increased in importance in the last 15 years, competitive tensions have merged between these private businesses and public sources of similar services - the agricultural extension agents.

5.5.3. Local groundwater management - How the system works

To what degree are information systems coordinated across scales?

In terms of technical useful information for farmers, the information system is well coordinated across different levels of scale. Texas A&M and its satellite research and experiment stations coordinate their research programs and are responsive to needs at the local level. HPUWCD, NRCS, the extension service, and private firms all provide a vast array of information that is retrieved from both on-the-ground research and through collaboration with area and state research institutions. HPUWCD has been an instrumental player in fostering collaboration between these agencies. In addition, the advisory board mechanisms of the extension service and NRCS, as well as the face-to-face contact between extension agents, NRCS agents, agricultural consultants, input sales representatives and farmers, facilitate the flow of information needs to the producers of information.

Unlike GMD#3 in Kansas and URNRD in Nebraska, HPUWCD has a highly trained technical staff which has some of the modeling expertise and technical background that is found in the Kansas Geological Survey or UNL’s Conservation and Survey Division. In addition, TWDB undertakes some of the function of a state geologic survey and HPUWCD and TWDB collaborate extensively on modeling exercises and management scenario testing. As such, USGS
is not consulted to a large degree, though it still provides some data to TWDB for its modeling efforts. The primary cross-scale links, therefore, are between HPUWCD and TWDB which effectively coordinate their research, data, and analysis needs and, as in Kansas and Nebraska engage in a dynamic assessment process.

To what degree are decision systems coordinated across scales?
Decision making has not been well coordinated across scales. The history of the state courts’ adherence to the absolute ownership doctrine and the legislature being unable to alter the doctrine have constrained local management districts from making regulatory decisions that might otherwise be in the district’s interest. In addition, it has only been recently (October 1997) that an earnest effort at regional and statewide planning has been coordinated at the state level. At the local level, there is significant distrust of state-level activity and regulation and there is little presence of state government felt at the local level.

To what degree are the information and decision systems integrated?
At the level of the HPUWCD, information and decision systems are fully integrated. Assessment of depletion of the aquifer and the policy process are intertwined, especially in an office which is characterized by both technical and policy expertise. Likewise at the state-level, the TWBD combines both its technical and policy processes in the water planning process. However, since ultimate decision making about groundwater utilization resides in the individual landowner, and not in state or local agencies, the information system which analyzes aquifer behavior and potential management scenarios (state level) is not well integrated into the decision making (individual level).

To what degree are multiple issues linked in the management system?
Historically, HPUWCD has dealt primarily with underground water supply issues. Given the paucity of streams in the region, interactions with surface water is a minimal concern. Only recently has it begun addressing water quality issues, and it is beginning to work more closely with TNRCC. Prompted by the recent Texas Senate Bill 1, HPUWCD has begun collaboration with TTU in helping guide a regional water plan. It has also embarked on a program, also in collaboration with TTU researchers, in exploring precipitation enhancement (primarily through cloud seeding) research and development. The district does not address wildlife and habitat issues or wetlands concerns which are impacted by groundwater use.

5.5.4. Local groundwater management - Is it effective?

Management environment
Given the relationship between state law, individual water rights, and the powers of HPUWCD, the management environment is one that is not conducive to rule making. Local management districts are constrained in the actions they may take and there is little ability to regulate to control the externalities (both in space and in time) that result from aquifer depletion. However, the limited rule making that has been implemented in the district has been strongly enforced by the courts.

Information capacity
What the HPUWCD lacks in regulatory ability it makes up in information capacity. Under the leadership of a dynamic manager who has held the position for 20 years, the district has forged positive long-term working relationships with extension, agricultural research stations, NRCS and private firms. These relationships have resulted in a huge array of methods for educating the groundwater users in the district. The district has been innovative in developing programs such as an on-farm irrigation efficiency evaluations in which a team of technicians from the district travel to a farm to assess the irrigation efficiency of the current system and to propose alternative solutions. As a source of information, the district is highly regarded by its constituents as a credible and useful source of information, both about the state of the aquifer, and irrigation management.

Management actions
The primary management actions that HPUWCD has undertaken has been education (see above) and technology cost-share programs. Using its limited powers established by statute, it has also regulated well spacing, water waste (it has banned tailwater waste - water that flows off of a field) and instituted limited pollution prevention measures (see Table 2).

6. COMPARATIVE RESULTS

6.1. A comparison of institutional variables

All three study sites have, in general, similar management structures: locally elected management districts embedded in a larger state management system supported by a well coordinated local, state, federal agricultural information system. Despite these similarities, a comparison of the functioning of the three systems reveals differences in how each system manages the aquifer. The differences in characteristics of the information and decision systems, those identified as the explanatory variables of the study, are summarized in Table 3. The descriptors of “low”, “medium”, and “high” are meant only to be relative, providing a qualitative assessment of the degree to which the management systems incorporate that variable.

All three study areas demonstrate a high degree of cross-scale coordination of information systems and a high degree of two-way communication between producers and users of agricultural and water-related information.

The largest variance between the three locales (and the state systems in which they reside) is in the degree to which decision systems are coordinated across scales. There is a relatively high degree of coordination in Nebraska where the state legislature, state courts, state agencies and the local Natural Resource District orchestrate their decision making and have institutionalized ways to avoid making decisions at one level that constrain decision making at other levels. While Kansas has similarly institutionalized cross-scale coordination of decision making, there are still discordant aspects of the system. For example, there has been poor coordination around the role of enforcement, and neither state nor local institutions have undertaken enforcement activities. In Texas, lack of decision making coordination has been institutionalized through water rights laws which constrain local management regulatory efforts. This has not constrained, however, other management efforts, such as education or cost-share incentive programs.
In both Nebraska and Kansas, the information and decision systems are well integrated with one another. At both local and state levels, decision making and information functions are either housed in the same organization where there is constant and iterative communication between technical staff and policy staff (or those functions reside in one person), or there is close collaboration in an ongoing fashion between agencies. In Texas, while this kind of integration is seen within the local management district, and within the state-level agencies, there is somewhat of a disconnect between the two levels in terms of information and decision making functions. Furthermore, with the majority of decision making power residing in the individual landowner, there is not as great an opportunity to integrate information and decision making functions.

Finally, of the three systems, the Nebraska system of NRDs, which have been granted broad management mandate with the responsibility of collaborating with state agencies, provides an institutional framework that requires linking related issues within the management process. While the management districts in Kansas and Texas were initially designed as single issue agencies, their mandates have been expanding in an ad hoc fashion, and their responsibilities are widening to cover more natural resource and environmental problems other than groundwater supply. At present, however, little linkage between groundwater and surface water, and water quantity and water quality exists in Kansas and Texas.

6.2. A beginning understanding of effective cross-scale management of the aquifer

Table 4 summarizes the differences in indicators of effective management in the three study sites. As in the comparison of institutional variables, the notation of “low”, “medium”, and “high” is meant to qualitatively capture the relative differences between these three regions.

Information capacity

All three study sites appear to have high information capacity and the production, transfer, and use of information is accomplished effectively in these three systems. It appears that the high degree of the institutional variables associated with information (coordination of information systems across scales) is, not surprisingly, associated with high information capacity. For example, cross-scale information coordination might contribute to increased information capacity in three ways. First, it allows information which is produced at one level of scale to be efficiently transferred to a different level of scale. The users of information (e.g., farmers or managers) routinely use institutionalized channels of communications between researchers, extension agents, and farmers and other actors such as management districts, the Natural Resources Conservation Service, and private firms. Second, and perhaps more important, it allows for the exploitation of comparative advantage of information production at different levels of scale. This is seen, for example, where all three local districts collaborate closely with federal or state agencies which can harness economies of scale and thus have the technical capacity to model changes in the aquifer, using locally collected data to drive the models. Third (and related to the previous two), long-term coordinated efforts have resulted in the development of trust between actors at different levels of scale. Ongoing personal relationship which bridge scale have allowed credibility of sources of information to grow. Federal and state agencies, for example, have gained this trust.
by hiring local people to fill their field offices and by responding to local needs. (Other federal agencies, such as the EPA, has not been as successful in fostering this trust.).

The institutionalization of two-way communication of needs and products also contributes to this evolution of trust, particularly when it is apparent that researchers are basing their decisions on the input from stakeholders at lower levels of scale. The two-way communication, also ensures that timely, usable and relevant information is produced for decision makers. In this regard, information translators or brokers have served an important role in this dynamic. The need for translators is highlighted in the recent shift from the farmers’ reliance on public sources of information to private sources. Several potential reasons have been identified that might explain this shift. First, the amount of information about seed hybrids, irrigation technologies, and chemicals has risen to the point where county extension agents no longer have the resources and capacity to learn about and disseminate information about current products and practices. At the same, budgetary constraints have become more salient for the agricultural research and extension system (CSREES). In real dollars, total spending on agricultural extension has been decreased over the last ten years (see Figure 10). Thus, conditions were ripe for the ascendancy of a private sector supplier of information that could satisfy the demand for information. Interestingly this rise in the importance of the private sector has further demonstrated the importance of public (and state-level) production of information. For example, agricultural consultants and input providers (e.g., seed producers) still rely on basic and applied research that is done in the land-grant college system. Recent collaborations between the R&D divisions of these input providers and university researchers also demonstrate this evolving relationship between the public and private sectors, and the importance of exploiting comparative advantages - e.g., private firms have a smaller capacity to undertake basic research than do university researchers.

Finally, the high level and specific form of the information capacity, particularly in Kansas and Nebraska, allows for more effective monitoring of the resource, an important characteristics of managing a resource with common pool attributes and the possibility of free-riding. Clearly, this aspect of information capacity is closely related to another indicator of effective management, the status of the management environment, and is addressed in the following section.

Management environment:
The management environment indicator of effectiveness is complex, multi-faceted and, as noted above, linked with the other indicators and variables studied. A system like that in Nebraska which coordinates well across scales in information and decision making, integrates the information and decision making process and addresses linked issues seems to be better able to address a multi-scale problem such as depletion of the High Plains aquifer. Coordination of decision making across scales, for example, might enable managers to avoid situations in which legislative action constrains decision making at local levels, or in which legislation unwittingly provides incentives that run counter to local and state management goals (as was the example of corn subsidies in the 1985 Farm Bill). Lack of coordination can also lead to decision making at lower levels of scale that cause higher scale problems - depletion of the aquifer itself is an example of this kind of dynamic. In addition, coordination across scales allows for rule making at a lower level that will be consistent with the state legal system. Where coordination is lacking,
the management environment might not be conducive to rule making. Finally, as long term coordination has the potential to establish long term trust-based relationships between actors who can find mutually beneficial ways of addressing a problem with common origins.

Integrating information and decision processes can lead to a conducive management environment by facilitating transparency and broader participation in the process. This integration also allows the fine-tuning of the information needs of decision makers with the producers of information. Thus, in systems in which information and decision making functions are integrated, there is less likely to be disjunction between assessors and decision makers.

The explicit linkage of related issues in the management system can also contribute to a conducive management environment for three reasons. First, in natural systems, different resources are linked through complex interactive pathways. If a management system does not account for these natural linkages, the management system can become unstable and there will be an increased likelihood that unforeseen problems will emerge. Second, linking issues has the potential of raising the relevance of the problem for actors who are potentially affected. As it has been shown that surface water and groundwater interacts, and as institutions have been charged to deal with the simultaneously, surface water irrigators have become much more interested and engaged in solving the groundwater depletion problems. Third, economies of scale exist that can be exploited. Groundwater Management Districts in Kansas already have in place the institutional structure for managing groundwater supply, and thus can channel that institutional capability into addressing water quality issues better than perhaps a new and different agency.

Finally, the management environment is influenced by information capacity for a wide range of reasons. One reason that is particularly important in addressing the common pool resource attributes of the aquifer is the following: A strong information capacity facilitates the monitoring of various aspects of the management regime - from the status of the aquifer to the compliance of landowners to regulations. This monitoring has the effect of raising concern about the resource, where it otherwise would not be raised. Additionally, this kind of monitoring can improve the contractual environment, providing a means by which “shirkers” (overpumpers or wasters, in this case) can be identified. The requirement of meters in Kansas and Nebraska and water use reports, combined with the public access to metering and usage information in all three states serve this function, and may both inhibit non-compliance and facilitate identification and censure.

Management actions
Management actions in the three study sites are summarized in Table 2. While all three areas have active educational and cost-share programs, only in Kansas and Nebraska have significant regulatory actions been taken. These regulatory actions have primarily involved pumping limits, meter requirements, conjunctive use requirements, and moratoria on new wells in particularly high risk areas. Interestingly, the regulations regarding “pooling” and “banking” in Upper Republican Natural Resource District in Nebraska is an effort to address a cross-scale problem that has negatively affected local management districts. In all three states, some version of a “use-it-or-lose-it” state law exist (either de facto or de jure), providing incentives for local landowners to be inefficient with their resource. The pooling and banking provisions attempt to avoid this incentive structure. Both have been upheld in Nebraska state courts.
7. CONCLUSIONS

7.1. Information and decision systems for cross-scale environmental problems

Like many newly emerging environmental problems, depletion of the High Plains aquifer is characterized by a resource, human impacts, and potential responses which spans a range of spatial scales. This research was a beginning effort to identify what characteristics of information/assessment and decision systems contribute to effective management of such a resource, specifically in regards to overcoming barriers imposed by scale-related boundaries.

Preliminary and tentative evidence gathered in this study supports the following general postulates. Management institutions and processes which address cross-scale problems can be effectively supported by information and decision systems which:

1) coordinate information systems across different scales - Coordination of information systems across scale can lead to effective management by facilitating the flow information and needs between producers and users, by creating networks of engaged stakeholders, by exploiting scale-related comparative advantages in information production and dissemination, by supporting monitoring, and by creating a climate of trust between actors at different levels of scale. (Because of the lack of variance between the cases in this study - all sites have a high degree of coordination across scale - this postulate is the least supported by the evidence and will require expansion of the cases - see the next section.)

2) coordinate decision making across different scales - Coordination of decision making systems across scale can lead to effective management by avoiding conflicting actions at different scales, exploiting scale-related comparative advantages in decision making functions, and creating a climate of trust between decision makers at different levels of scale.

3) integrate decision making and information functions across different scales - The integration of decision making and information functions can lead to effective management by facilitating the incorporation of scientific information into the decision making process. Through this kind of integration assessments can be better tailored to the needs of the user of the assessment. This integration also highlights the process aspects of assessments in which assessments are far more dynamic than the production of a report. In fact, while written reports are completed about the impacts of and responses to depletion of the aquifer, it is the ongoing collaborative process of model building, testing, and data collection which characterizes “assessment” in these three areas. This notion is consistent with recent research which has characterized assessments as communicative social processes (Miller, Jasanoff et al. 1997)

7.2. The next phase of this research

By limiting the study sites that share the institution of a local groundwater management, and which share similar levels of risk, I am unable to complete a causal analysis which can fully describe (or even confidently identify the direction of causality) the causal pathways which lead
to effective management. Rather, this phase of the research points to tentative hypotheses about cross-scale coordination and information/decision making integration, captured in the descriptions in the previous section, that can be better tested by broadening the scope of the sites, and examining other indicators of effective management.

In the next phase, I will select two more sites in each state to increase the institutional and natural variance, choosing low and medium risk sites, and sites which do not have local groundwater management districts. In addition, a more historical approach will be taken in which information and decision making variables and management changes can be mapped over time. Furthermore, the next phase of research will track other indicators of management effectiveness further down the causal chain including: behavioral changes (such as the adoption of water efficient technologies); and measures of the state of the aquifer (changes in saturated thickness, changes in depletion rates, etc.).

Preliminary evidence indicates that this approach might be fruitful. Figure 11, for example, illustrates the adoption of the center-pivot irrigation system (a highly efficient system) in two counties in Texas. Lamb County, which is in an Underground Water Conservation District, and Swisher County which is cattycorner to Lamb (and thus shares much of its natural, social, and economic characteristics), but it is not part of a UWCD. Two tentative reasons might explain the significant difference in the rates of adoption. First, is the educational services provided by High Plains Underground Water Conservation District that is partly lacking in Swisher County (“partly” because of the public good nature of this information). The second relates to the cross-scale coordination that HPUWCD engages with the Texas Water Development Board, a major source of cost-share funding. Swisher County lacks this coordination with TWDB, and thus does not participate in many of the cost-share programs that are available to farmers in Lamb County. Of course, causality might be operating in the other direction, where farmers in Swisher do not care about conservation of the resource and thus vote not to be in HPUWCD.

Additionally, the next phase of this research will more explicitly address how the lessons learned from this analysis can be applied to addressing climate change. I will conduct a more rigorous analysis, for example, of how the attributes of aquifer depletion is analogous to climate change, and identify what aspects of the information systems in the High Plains would be desirable or transferable to the climate change arena.

Finally, while this paper has focused primarily on how the boundaries defined by different scales can be bridged, other boundaries are clearly important as well, and in fact may dwarf the impact of cross-scale barriers. Further research will characterize these other boundaries and try to identify how the lessons about dealing with cross-scale dynamics can or cannot map onto other boundaries. For example, the research/application boundary that exists in the agriculture has often acted as a obstacle to information flow. Further extension of the research will examine how innovations such as those seen in Kansas where the research and extension services have been merged, influence management effectiveness. Another boundary which this paper has addressed (however minimally) is the socially constructed boundaries which define environmental issues (e.g., groundwater quantity v. groundwater quality). Future research will explore the kinds of advantages and disadvantages to the construction of such barriers and how crossing these barriers influences the efficacy of management.
REFERENCES


Nebraska Department of Water Resources (1996). Fifty-first biennial report. Lincoln, NE, Nebraska Department of Water Resources.

Nebraska Natural Resources Commission (1986). Base document of the Nebraska soil and water conservation strategy. Lincoln, NE, Nebraska Natural Resources Commission.


Texas Senate Bill 1 (1997). “An act relating to the development and management of the water resources of the state.”


### Table 1 - Management actions

<table>
<thead>
<tr>
<th>Management action</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well-spacing requirements</td>
<td>limit of distance between wells</td>
</tr>
<tr>
<td>Permit for well</td>
<td>a permit is required for the drilling of a new well</td>
</tr>
<tr>
<td>Local tax to support district</td>
<td>a tax is levied on a acreage basis</td>
</tr>
<tr>
<td>Cost-share programs</td>
<td>the district, through grants, provides funds for the adoption of water efficient technologies</td>
</tr>
<tr>
<td>Education(newsletters, seminars,</td>
<td>the district communicates to farmers through a variety of media about the condition of the aquifer, new techniques etc.</td>
</tr>
<tr>
<td>radio, TV, etc.)</td>
<td></td>
</tr>
<tr>
<td>irrigation evaluations</td>
<td>evaluations of a farmers irrigation system are provided to farmers by the district</td>
</tr>
<tr>
<td>Ban on tailwater waste</td>
<td>the banning of water that runs off a field after it has been irrigated</td>
</tr>
<tr>
<td>Conjunctive use requirements</td>
<td>regulations based on the interaction of ground and surface water.</td>
</tr>
<tr>
<td>Moratoria on new wells</td>
<td>ban on new wells, usually in a specified area which has experience excessive depletion</td>
</tr>
<tr>
<td>Meter requirement</td>
<td>requirement of meters on pumps</td>
</tr>
<tr>
<td>Mandatory report of water use</td>
<td>requirement of farmer to report water use</td>
</tr>
<tr>
<td>Designation of critical areas</td>
<td>designation of areas that are in critical need of management because of high levels of depletion (these areas may then be subject to more strict regulation)</td>
</tr>
<tr>
<td>Permit for water quantity (one</td>
<td>permit that defines amount of water farmer can use, set at the time of permitting</td>
</tr>
<tr>
<td>time only)</td>
<td></td>
</tr>
<tr>
<td>Permit for water quantity</td>
<td>permit that defines amount of water farmer can use, set periodically in response to state of the aquifer</td>
</tr>
<tr>
<td>(variable)</td>
<td></td>
</tr>
<tr>
<td>Enforcement (fines, cease and</td>
<td>actions to enforce regulations</td>
</tr>
<tr>
<td>desist orders, etc.)</td>
<td></td>
</tr>
<tr>
<td>Chemical application permit</td>
<td>requirement of training and permitting in order for a farmer to apply chemical fertilizer or pesticides through an irrigation system</td>
</tr>
<tr>
<td>Water &quot;banking&quot;</td>
<td>the transference of allocated water over time, either by the farmer to him/herself, or to a new landowner at the time of sale of the land.</td>
</tr>
<tr>
<td>Water &quot;pooling&quot;</td>
<td>a farmer can &quot;pool&quot; all of his/her water allocations and distribute that allocation as he/she sees fit throughout all of his/her land holdings</td>
</tr>
</tbody>
</table>
### Table 2 - Management actions - comparison

<table>
<thead>
<tr>
<th>Management actions</th>
<th>Kansas (Finney Co.)</th>
<th>Nebraska (Chase Co.)</th>
<th>Texas (Lamb Co.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well-spacing requirements</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Permit for well</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Local tax to support district</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Cost-share programs</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Education (newsletters, seminars, radio, TV, etc.)</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>irrigation evaluations</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Ban on tailwater waste</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Conjunctive use requirements</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Moratoria on new wells</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Meter requirement</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Mandatory report of water use</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Designation of critical areas</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Permit for water quantity (one time only)</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Permit for water quantity (variable)</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Enforcement (fines, cease and desist orders, etc.)</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Chemical application permit</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Water &quot;banking&quot;</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Water &quot;pooling&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3 - Institutional variables

<table>
<thead>
<tr>
<th>The degree to which:</th>
<th>Kansas (Finney Co.)</th>
<th>Nebraska (Chase Co.)</th>
<th>Texas (Lamb Co.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>information systems are coordinated across scales</td>
<td>high</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>decision systems are coordinated across scale</td>
<td>medium</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>information and decision systems are integrated</td>
<td>high</td>
<td>high</td>
<td>medium</td>
</tr>
<tr>
<td>linkages between resource issues are addressed</td>
<td>medium</td>
<td>high</td>
<td>medium</td>
</tr>
</tbody>
</table>

Table 4 - Indicators of effective management

<table>
<thead>
<tr>
<th></th>
<th>Kansas (Finney Co.)</th>
<th>Nebraska (Chase Co.)</th>
<th>Texas (Lamb Co.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conducive management environment</td>
<td>medium</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Information Capacity</td>
<td>high</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Management actions</td>
<td>medium</td>
<td>high</td>
<td>medium</td>
</tr>
</tbody>
</table>
FIGURES

Figure 1 - High Plains aquifer (from (Glantz 1988)
Figure 2 - Study sites
Figure 3 - Local management districts that cover the three study sites
**Figure 4 - Saturated thickness of the High Plains aquifer, 1980** (adapted from (Kromm and White 1992))
Figure 5 - Total groundwater irrigated acres in the High Plains region 1949-1990

Derived from (McGuire and Sharpe 1997)
Figure 6 - Water-level declines in the High Plains aquifer, 1980-1995 (from U.S. Geological Survey, 1997).
Figure 7 - Groundwater Management Districts (GMDs) in Kansas

Figure 8 - Natural Resource Districts (NRDs) in Nebraska
Figure 9 - Underground Water Conservation Districts (UWCDs) in Texas

EXPLANATION
1. Dallas County Underground Water Conservation District No.1
2. North Plains Ground Water Conservation District No.2
3. Panhandle Ground Water Conservation District No.3
4. High Plains Underground Water Conservation District No.1
5. Sandy Land Underground Water Conservation District
6. South Plains Underground Water Conservation District
7. Texa Underground Water Conservation District
8. Permian Basin Underground Water Conservation District
9. Glasscock County Underground Water Conservation District
Figure 10 - Normalized trends in expenditures for Agricultural Extension Services Kansas + Nebraska + Texas; 1988-1996 (adjusted for inflation)

Figure 11 - Adoption of water center-pivot (water efficient) irrigation systems, Lamb and Swisher Counties, Texas
APPENDIX - INTERVIEWEES

Kansas

Associate Director for Public Outreach - Kansas Geologic Survey, Lawrence.
Director - Kansas Water Office, Topeka.
Hydrologist - Division of Water Resources, Kansas Department of Agriculture, Topeka.
Special Environmental Assistant to the Secretary - Kansas Department of Agriculture, Topeka.
Professor of Geography, Water Resources Management Specialist - Kansas State University, Manhattan.
Professor of Climatology and Applied Geography - Kansas State University, Manhattan.
President - Finney County Farm Bureau, Garden City.
Assistant Professor, Agricultural Engineer - Kansas State University, Southwest Research-Extension
Center, Garden City.
General Manager - Servi-Tech (agricultural consultant), Inc., Dodge City.
Area Engineer - Natural Resources Conservation Service, Dodge City.
Member, Board of Directors (elected) - Groundwater Management District #3, Garden City.
Executive Director - Groundwater Management District #3, Garden City.
Resource Conservationist -Groundwater Management District #3, Garden City.
Manager - Gigot Irrigation, Inc., Sublette.
Water Commissioner, Garden City Field Office - Division of Water Resources, Kansas Department of
Agriculture, Garden City.
Finney County Extension Agent - Kansas State University, County Research and Extension, Garden
City.

Nebraska

Director of Natural Resources - Natural Resources Commission, Lincoln.
Head, Comprehensive Planning - Natural Resources Commission, Lincoln.
Engineer, Planning Division - Natural Resources Commission, Lincoln.
Permits and Adjudications - Department of Water Resources, Lincoln.
Field Sales Agronomy Manager - Pioneer Hi-Bred Inc. (seed company), Lincoln.
Hydrogeologist - Conservation and Survey Division, Institute of Agriculture and Natural Resources,
University of Nebraska, Lincoln.
Extension Specialist - Water Resources and Irrigation, Institute of Agriculture and Natural Resources,
University of Nebraska, Lincoln.
Master Breeder - A large multinational agricultural input firm.
District Conservationist - Natural Resources Conservation Service, Imperial.
Director - Upper Republican Natural Resource District, Imperial.
Member, Board of Directors (elected) - Upper Republican Natural Resource District, Imperial.
Certified Professional Agronomist (independent agricultural consultant), Imperial.
Extension Educator - University of Nebraska Cooperative Extension, Southwest Four Extension
Programming Unit, Imperial.
Texas

Director, Water Resources Development Division, Texas Water Development Board, Austin.
Assistant Division Director, Water Resources Development Division, Texas Water Development Board, Austin.
Professor of Agricultural Economics, Texas A & M University, College Station.
Professor of Crop Physiology - Plant and Soil Sciences Department, Texas Tech University, Lubbock.
Director, Water Resources Center/Professor of Civil Engineering - Texas Tech University, Lubbock.
Associate Professor - Soil Physics - Texas Agricultural Experiment Station - Texas A&M University, Lubbock.
Agronomist/Entomologist (independent agricultural consultant), Lubbock.
Assistant State Conservationist (field operations) - Natural Resources Conservation Service, Lubbock.
Manager - High Plains Underground Water Conservation District No. 1, Lubbock.
Regional Director - Texas Department of Agriculture, Lubbock.
Senior Marketing Specialist - Texas Department of Agriculture, Lubbock.
Chief Inspector, Pesticide - Texas Department of Agriculture, Lubbock.
Environmental Investigator, Field Operations Division - Texas Natural Resource Conservation Commission, Lubbock.
Member, Board of Directors (elected at-large) - High Plains Underground Water Conservation District No. 1, Anton.
Member, Board of Directors (elected) - High Plains Underground Water Conservation District No. 1, Littlefield.
President - Spade Co-op Inc., Spade.
Lamb County Extension Agent - Texas A&M University, Littlefield.

Federal Government

National Water Management Engineer - US Department of Agriculture, Natural Resources Conservation Service, Conservation Engineering Division, Washington, DC
National Program Leader-Animal Genetics - US Department of Agriculture, Cooperative State Research, Extension, and Education Service, Plant and Animal Systems, Washington, DC
Director - National Drought Mitigation Center, Lincoln, Nebraska.