Kansas Geological Survey

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Scale, uncertainty, and the relationships between basic data, information, and management perspectives

By

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With contributions from other authors in the report series

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KGS OFR 2002-25F. Scale, uncertainty, and the relationships between basic data, information, and management perspectives

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1. Introduction

1.1 Objectives:

This report addresses information relevant to two slightly different formulations of the same issue addressed as the final substantive point in both the KWO and KDA contracts (Appendix A, KGS OFR 2002-25A). KWO: “The appropriate scale of use and precision of data sets identified during the quarterly meetings.” KDA: “Data reflecting the appropriate balance or interface in scale between basic data (sub township) and basic information (township) and management perspective.”

These issues have been grouped under two general headings. ‘Scale’ refers to the size of an interval of either space (distance, area or volume) or of time. The scales of models or measurements are important in considering appropriate applications, or in combining different kinds of information. For example, the information acquired by making a measurement at hourly or daily intervals is quite different from that obtained by monthly or annual observations. Similarly, knowledge of the same parameter based on observations at the scale of miles, tens of miles and hundreds of miles are related, but can be quite different in their accuracy, precision, and potential applications. ‘Uncertainty’ is the technical term used to discuss ways to deal with the fact that all knowledge is imprecise or uncertain at some level; measuring or estimating uncertainties (which are often a function of scale) is an important step in deciding how to use data and information. It should be recognized that all measured data are simply representations of or provide a model for natural conditions and/or phenomena. As such, data will always have some level of uncertainty in their representation. The question then becomes, is that uncertainty at a level that changes the goals or implementation of management and analysis considerations.

The purpose of the discussions presented in the following sections is to provide some basic background on terms, concepts, and available data, and then to examine their application to specific issues related to the identification and management of aquifer subunits that can be selected on the basis of internal similarity and the expected lifetime of the water resources. An important component of evaluating data quality and uncertainty is knowledge about the data and how it was acquired or processed. The information providing this knowledge is often called ‘metadata’ and is also described and discussed in this report.

1.2 Scientific and management scales

Human decisions are implemented on the basis of legal and political boundaries, while scientific characterization follows natural boundaries and gradients that often do not coincide with social conventions. How can these two approaches be reconciled in developing a more scientifically based approach to managing groundwater resources? The boundaries of the Groundwater Management Districts provide an example; because the hydrogeologic limits of the aquifer formation do not coincide with county boundaries, township and section boundaries are used to approximate the aquifer extent in terms of units that are well defined by the Public Land Survey System (PLSS).

Hydrologists, geologists, and geographers commonly use grid systems to describe and calculate spatially distributed characteristics. To be effective, a grid-system used should be fine enough (that is, have small enough grid cells or 'boxes') so that it can adequately represent the highest resolution data set or application. In the case of ground-water resources, pumping wells have zones of influence that typically extend a half-mile or more in all directions from the well (see section 4.3 below). This defines a distance of about a mile, or an area of about one section, as a practical lower limit of resolution for most purposes. A grid based on PLSS sections is not exactly identical to a perfect square-mile grid, but it is close enough so that scientific conclusions are not significantly distorted by treating it as a square-mile grid, and its use ensures that results are presented in a form that is directly recognizable and usable for public information and management.

The KGS has developed a section-based grid for presenting and analyzing water and hydrogeologic data that has been used in a variety of research and analysis projects such as the Atlas of the Kansas High Plains Aquifer (http://www.kgs.ukans.edu/HighPlains/atlas/). This internet-accessible database is described, along with information on accessible point-data and time series databases, in section 2.1 below. Section-level data is a convenient, consistent medium for exchanging and applying information, and provides the basic 'building blocks' for addressing larger areas. Some data are available at the section level or even finer – water use, elevation, and soil type, for example. Other data, such as depth to bedrock and precipitation, may be available or appropriate to use at that resolution in some areas, but not everywhere. Many types of data are available from much coarser resolution observations that must be interpolated or aggregated from point sources to obtain section level values between the measuring sites (examples include climate data, discussed in OFR 2002-25E, and water-level data, considered in section 4 of this report).

Because of the variety of the data sets available at this present date that contribute to the section-level database, and the uncertainty at the section level of those values that are interpolated from much more widely-spaced observations, there is general agreement that management applications of the data should be at the scale of tens of square miles. This is referred to as the township level, since a 36 square mile township is about the minimum size appropriate for application of some of the present data sets. However, this term is not meant to imply that legal township boundaries should be used. Rather, an assembly of similar, contiguous sections adding up a total area of that magnitude (or greater) should be the goal of subunit definition on the basis of the existing data.

2. Data and Metadata

2.1 Data availability and applicability, present and potential

2.1.1 Tools and access

The Kansas Geological Survey, and the closely associated Data Access and Support Center, have a long-term goal of making electronic data and information readily available to the citizens and agencies of Kansas. Beginning with the production of the High Plains Atlas (Schloss et al., 2000), a database of water-related variables gridded by legal section has been under development and has been available on line in prototype form. The present version can be accessed from the "section-level data" link at http://www.kgs.ukans.edu/HighPlains/data_access.html. It permits selection of geographic areas by GMD or latitude-longitude (plans are in place to add extended spatial query capabilities such as township-range-section), visualization of data selections to determine completeness and range and distribution of values, mathematical transformation or filtering of data sets, correlation analysis, and data download or cluster analysis in the electronically linked LoiczView on-line program (http://www.palantir.swarthmore.edu/loicz/help).

In addition to this consistently gridded spatial data set, another prototype development makes time-series data available at the individual well and legal section level. These are available from the prototype access page accessible at (http://www.kgs.ukans.edu/HighPlains/Dywix_intro.htm) (or via the "Time-Series Data" link on the High Plains data access page). The database can be searched by GMD, county, township-range-section, or latitude and longitude, but in the present version the data can be accessed only via individual well records, one well (or the corresponding legal section) at a time.

2.1.2 Data availability

2.1.2.1 Time series

The data access tool (http://www.kgs.ukans.edu/HighPlains/Dywix_intro.htm) is based around the KGS Wizard database; it provides time-series plots (or data downloads) of water level measurements on selected wells, plus access to the other aquifer and well information contained in the Wizard database. In addition, linked databases provide concurrent download and visualization of water use and irrigation summary data (extracted from the WRIS database for the period 1990-1999; see section 2.2 below) for the section identified, and monthly water balance data from the Wilmott-NCDC data set (Wilmott and Matsuura, 2001) described in report OFR 2002-25E (1950 through 1999 precipitation, potential evapotranspiration, evapotranspiration, surplus, deficit, and soil mosture).

The individual well water levels and well-based information are usable at the local (section or smaller) level, as are the water use data. The climatic water balance data are appropriate for annualized estimates at the township-to-section scale.

The inclusion of temporal statistics in the geospatial database (see below), such as range and standard deviation of the values over a given period, provides additional insight into the temporal variability of the parameters.

2.1.2.2 Gridded section-scale databases

Table 1 is based on the variable selection list from the High Plains Aquifer database website. It presents current data availability in ordinary text, and lists feasible additions (that, is data presently available or readily obtainable on a time scale of a year or less) in **Impact** type font. The variables are coarsely grouped together into common themes and types of variables.

Column A indicates time scale of potential availability: 0 = presently contained in database; 1 = could be included on a time scale of 3-4 months or less; 2 = could be included on a time scale of 6-8 months or less; 3 = could be included within one year. It is important to note that these times refer to **individual variable additions**; the combined effort associated with all items listed as 1 is far too great to update the database with all of them on a time scale of 3-4 months with presently available resources. Another important factor is the need to select a relatively small number of scenarios for implementation; for example, the choice of a wide range of pumping rates and hydraulic conductivities could result in an unmanageable number of yield-based lifetime estimates.

Column B indicates the appropriate analysis scale for application of the data; although all are presented as section-level values, many are derived from data sets with coarser resolution, and should only be used to assemble aggregated measurements at larger scales. T and S stand for Township and Section scales, used in the sense outlined in section 1.2 above and discussed in more detail in section 3 below. The + and – symbols indicate a variable that is intermediate in applicability; a T- evaluation indicates that the underlying data support higher resolution that a township, but not as fine as a section. A variable rated S+ might be appropriate for application to a two mile circle, but not an individual section, for example. These rankings are based on a combination of the metadata (see sections 2.1.2.3 and 2.2 below) and the professional experience of KGS staff in working with the data sets.

In the interests of conciseness, possible variable additions or updates that are the same as or closely related to existing variable are indicated in the same data row, using the distinguishing type face. New variables that are qualitatively different from those already available are shown in separate lines.

Table 1.1: Data gridded at section level presently **and potentially available from KGS**

Column A – availability code; see text for explanation

Column B -- Appropriate (smallest) scale of application: see text for explanation

A	B	Column Name	Variable	Select
Geographic and Geomorphic variables				
0	S	LONGITUDE	Section center Longitude (HPA)	☐
0	S	LATITUDE	Section center Latitude (HPA)	☐
1	**S**	**TOWNSHIP_RANGE_SECTION**	**PLSS identity of section**	
1	**S-**	**GROUND_ELEVATION (mean, max., min., std. dev.)**	**Section elevation statistics (USGS DEM) –** ***multiple entries, ft and m***	
0 **1**	S	TOTALAREA **[add square miles]**	Total area of section in square meters	☐
Hydrogeology and Aquifer Characteristics				
0	T-	SPEC_YLD	Specific yield (USGS)	☐
o 1	T-	HYDR_COND **[update with new interpolation routine]**	Hydraulic conductivity (USGS)	☐
0	T-	BDRK_ELEV	Bedrock elevation (USGS with minor WWC5 enhancements by the KGS)	☐
2	**S+**	**AVG_MIN_SOIL_PERM [other variables available]**	**Section average permeability of least permeable soil layer (NRCS/KGS)**	
2-3+	**S**	**LOCAL_BDRK_ELEV [GMD or subunit level]**	**New or enhanced bedrock surveys**	
Note: spec_yld and hyd_cond may also be upgraded in selected areas, but probably not within a year				

Water Budget variables				
0 **1**	T-	TOTAL_PRECIP_MM **[update, w/statistics – mean, min., max., and std. dev.]**	Total Annual Precipitation, mm (HPA) [1950-1999]	☐
0	T-	TOTAL_PRECIP_IN	Total Annual Precipitation, inches (HPA)	☐
0	T-	PRECIP_NRM (would be replaced by statistics)	The calculated normal precipitation (1961 - 1990) (HPA)	☐
0 **1**	T-	PRECIP_SNL **[update, w/statistics – mean, min., max., and std. dev.]**	The (HPA) calculated normal seasonal precipitation (Mar-Oct),1961 - 1990)	☐
0 **1**	S	WUSE_AVG90 **[update, w/statistics – mean, min., max., and std. dev.]**	The average amount of water reported diverted from 1990 to 1999 (DWR-KGS) **[to most recent year available]**	☐
0	S	G_WUSE_AVG **[update, w/statistics – mean, min., max., and std. dev.]**	The average amount of ground water reported diverted from 1990 to 1999 (DWR-KGS)	☐
1	**S-T**	**Groundwater Use Density**	**Multiple values: 2, 5, and 10 mi smoothing**	
0	S	S_WUSE_AVG **[update, w/statistics – mean, min., max., and std. dev.]**	The average amount of surface water reported diverted from 1990 to 1999 (DWR-KGS)	☐
0	T+	USGS_RECHARGE	Recharge, estimated actual (USGS)	☐
?	**?**	**Aquifer discharge (not yet defined)**	**Apportionment of groundwater and surface water discharge across relevant aquifer units**	
0	T+	ST_PRE	Saturated thickness, predevelopment (HPA)	☐
0 **1**	T	ST_98 **[update to 2001 value]**	Saturated thickness, 1998 (HPA)	☐
0	T-	STOR_PRE	Water in storage, predevelopment (HPA)	☐
0 **1**	T	STOR_98 **[update to 2001 value]**	Water in storage, 1998 (HPA)	☐
0 **1**	T	DTW_98 **[update to 2001 value]**	Depth to water, 1998 (HPA)	☐
0	T	INV_DTW_98 [*drop – online calculation available*]	Depth to water inverse (1/ft), 1998 (HPA)	☐
0	T+	WLE_PRE	Water level elevation, predevelopment (HPA)	☐
0 **1**	T	WLE_98 **[update to 2001 value]**	Water level elevation, 1998 (HPA)	☐
Groundwater Dynamics – changes and trends				
0	T	WL_CHG_PRE_98	Water level change (ft), predev – 1998	☐

1		**[update to 91-01, 91-96, 96-01 values]**	(HPA)	
0 **1**	T	ATREND_88_98 **[update to 91-01, 91-96, 96-01 values]**	Water level annual trend (ft/yr) 1988-1998 (HPA)	☐
0	T	INV_ATREND_88_98 [*drop – online calculation available*]	Water level inverse trend (yr/ft) 1988-1998 (HPA)	☐
0	T	ATREND_78_88	Water level annual trend (ft/yr) 1978-1988 (HPA)	☐
0	T	INV_ATREND_78_88 [*drop – online calculation available*]	Water level inverse trend (yr/ft) 1978-1988 (HPA)	☐
0 **1**	T	ST_CHG_FT **[update to 2001 value]**	Saturated thickness change (ft), predev-1998 (HPA)	☐
0 **1**	T	ST_CHG_PCT **[update to 2001 value]**	Saturated thickness change (%), predev-1998 (HPA)	☐
0 **1**	T	STOR_CHG **[update to 2001 value]**	Water in storage change, predevel-1998 (HPA)	☐
2	**T**	**STOR_CHG_[91_01]** **[or period to match water use data]**	**Calculated change in water in storage, 1999-2001 [or other selected period]**	
Administrative, Planning and Management variables				
0	#	DWR_RECHARGE	Recharge, administrative (DWR)	☐
0 **1**	T*	FT_TO_DEPLETE (1998) **[update to 2001 value]**	Feet to depletion (Saturated thickness - 30') (HPA)	☐
1-2	**T**	**YIELD_FT_TO_DEPLETE**	**Feet above minimum sat. thick. per selected OFR 2002-25C scenarios**	
0 **1**	T*	YRS_DEPL_88_98 **[Update to, or add, 91-01 & 96-01 values]**	Years to depletion (1988-1998 trend) (HPA)	☐
0	T*	YRS_DEPL_78_88	Years to depletion (1978-1988 trend) (HPA)	☐
2	**T**	**YRS_DEPL_YIELD**	**Years to depletion based on selected trends and YIELD_FT_TO_DEPLETE**	
0	S	AUTH_QTY	The amount of water authorized to be pumped annually (as of June 25, 2001) (DWR-KGS)	☐
0	S	G_AUTH_QTY	The amount of ground water authorized to be pumped annually (DWR-KGS)	☐
0	S	S_AUTH_QTY	The amount of surface water authorized to be pumped annually (DWR-KGS)	☐
0	S	VNUM	The number of vested water rights within the section (DWR-KGS)	☐
0	S	G_VNUM	The number of vested ground water rights within the section (DWR-KGS)	☐
0	S	S_VNUM	The number of vested surface water rights within the section (DWR-KGS)	☐

0	T	AVAIL	Availability index (HPA)(1998)	☐
0	T	ACCESSIB	Accessibility index (HPA)(1998)	☐
Land Use and Land Cover (as of early 1990s)				
0	S+	OPEN_WATER	Percent section classed Open Water in USGS KS LULC	☐
0	S+	LOW_INTENS_RES	Percent section classed Low Intesity Residential in USGS KS LULC	☐
0	S+	HIGH_INTENS_RES	Percent section classed High Intesity Residential in USGS KS LULC	☐
0	S+	COMMERCIAL_INDUST_TRANS	Percent section classed Commerical/Industrial/Transportation in USGS KS LULC	☐
0	S+	BARE_ROCK_SAND_CLAY	Percent section classed Bare Rock/Sand/Clay in USGS KS LULC	☐
0	S+	QUARRIES_STRIP_GRAVEL	Percent section classed Quarries/Strip Mines/Gravel Pits in USGS KS LULC	☐
0	S+	TRANSITIONAL	Percent section classed Transitional in USGS KS LULC	☐
0	S+	DECID_FOREST	Percent section classed Deciduous Forest in USGS KS LULC	☐
0	S+	EVERGREEN_FOR	Percent section classed Evergreen Forest in USGS KS LULC	☐
0	S+	MIXED_FOREST	Percent section classed Mixed Forest in USGS KS LULC	☐
0	S+	SHRUBLAND	Percent section classed Shrubland in USGS KS LULC	☐
0	S+	GRASSLANDS_HERBAC	Percent section classed Grasslands/Herbaceous in USGS KS LULC	☐
0	S+	PASTURE_HAY	Percent section classed Pasture/Hay in USGS KS LULC	☐
0	S+	ROW_CROPS	Percent section classed Row Crops in USGS KS LULC	☐
0	S+	SMALL_GRAINS	Percent section classed Small Grains in USGS KS LULC	☐
0	S+	FALLOW	Percent section classed Fallow in USGS KS LULC	☐
0	S+	URBAN_REC_GRASSES	Percent section classed Urban/Recreational Grasses in USGS KS LULC	☐
0	S+	WOODY_WETLANDS	Percent section classed Woody Wetlands in USGS KS LULC	☐
0	S+	EMERG_HERBAC_WETLND	Percent section classed Emergent	☐

			Herbaceous Wetlands in USGS KS LULC	

2.1.2.3 Supporting information and development plans

The water- and geology-related data in the databases described are largely derived from the Wizard and WRIS databases, the metadata for which are discussed in section 2.2. Derived variables produced for the High Plains Atlas are described by Schloss et al. (2000), and the metadata for the Wilmott-NCDC climate data are given by Wilmott and Matsuura (2001).

Because the data sets come from disparate sources with a wide range in the quality and format of metadata and background information, a common-format, user-friendly metadata inventory will take substantial effort to develop. Ultimately, it is hoped that resources will be available to develop database access tools that have built-in links to standardized metadata; for an example, go to (http://www.kgs.ukans.edu/Hexacoral/Envirodata/envirodata.html) and login to the data base to see examples of access to multiple related databases, and source and variable metadata links from the selection table.

Also under development by funded projects are new tools and database 'front ends' that could be adapted to refine the High Plains prototypes. A particularly relevant project is construction of an expanded front end for the Wizard database, with expanded capabilities. Expected to be on line sometime in Fall, 2002, this version of the WIZARD database access web page will include new GIS capabilities as well as additional water level data processing and statistical review tools. By enabling the spatial characteristics of the WIZARD data, a potential expansion of this project is to adapt it to access the variables listed in Table 1 based on the selection results from the WIZARD front end. This would allow users the ability to incorporate actual well data and water level time series with additional data parameters. This is turn provides a better understanding of those trends in relation to each other and other characteristics of that location.

2.2 Metadata

The concept or term of "metadata" can best be described as data about data. Metadata is a collection of information that describes the content, quality, condition and other characteristics of data sets. It enables organizations to record and maintain important information about data, which in turn facilitates the sharing and understanding of that data by outside users. Metadata also serves as the mechanism to outline how or where the data were acquired, potential use limitation, recommended scales of use, and other unique parameters for not only the data set itself, but also the individual data elements within the data set.

As discussed before, every data set has some level of uncertainty associated with it; however, many data sets also have a particular set of "business" or relationship rules that must be followed when conducting analyses or calculations on that information. Unfortunately in many cases, the person charged with maintaining a particular data set is often the only one who is familiar with or recognizes these conditions. Personnel changes can lead to this information being lost if it is not systematically and accessibly maintained.

The Federal Geographic Data Committee (FGDC) is a federal interagency committee organized in 1990 to promote the coordinated use, sharing, and dissemination of geo-spatial data on a national level. From this effort a set of FGDC metadata standards was developed in 1994, which serves as the primary guidelines for metadata posted in many data clearinghouses throughout the country. There are several objectives and benefits behind having standards for metadata specifically. For example, a set of metadata standards provide a common set of terminologies and definitions for documents, help organize and maintain an organization's investment in data, and provide information to process and interpret data received by external sources.

Many of the data elements stored in the KGS section-level database came from a series of principal data sets maintained by state agencies. Specifically, the Water Information Storage and Retrieval Database (WIZARD) represent the primary repository on ground water level measurements in Kansas, the Water Well Completion Records (WWC5) Database contains information from records submitted by water well drillers to the Kansas Department of Health and Environment, and the Water Rights Information System (WRIS) contains information associated with water rights administered by the Kansas Department of Agriculture's Division of Water Resources.

These particular data sets were the foundation for the bulk of information currently stored in the KGS section-level database. For example, saturated thickness and changes in the water table over time were interpolated from data housed in WIZARD and WWC5, while reported water use and annual allocation information was obtained from WRIS. Maps like the estimated usable lifetime of the High Plains aquifer are products of analyses of data from these sources.

Given the importance and level of use of these data sets in understanding the aquifer system, FGDC compliant metadata was either created or updated for the WIZARD, WWC5, and WRIS data sources. The metadata files for WIZARD and WWC5 databases can be viewed at (http://www.kgs.ku.edu/Magellan/WaterLevels/wizard_fgdc.html**)** and (http://magellan.kgs.ukans.edu/WaterWell/wwc5_fgdc.html**)** respectively. Information pertaining to the data stored in the Water Information Management and Analysis System (WIMAS), which represent a commonly used subset of WRIS, is available at (http://gisdasc.kgs.ukans.edu/metadata/wimas.html**)**. A more detailed metadata file on the actual water rights data is stored within the WIMAS application.

With developed metadata files for these primary data sets, users have a resource that addresses several key questions and use requirements. Question that can be answered from the metadata files include: how and by whom were the data collected, when and here were the data collected, why were the data collected, and how and at what scale should they be used.

3. Spatial and temporal scales and variability

3.1 Background information

3.1.1 Notes on terminology:

1. The word "scale" has two different uses, which can generate confusion. We use the commonly understood definition of a "large-scale" feature as something that covers a lot of space and/or time (the Ogallala formation, for example) and a "small-scale" feature as something very local (like a specific location where a section of the Ogallala is exposed) or of short duration. However, in mapping (cartographic) terminology, the terms are reversed because they are applied to the 'scale' or display ratio of the map.

A 1:10,000,000-scale map is considered a small-scale map because ten million inches on the ground are represented by only one inch on the map (a small distance relative to what it represents). A 1:10:000 scale map is a large-scale map, because one inch on the map represents only 10,000 real inches -- a much larger scaling ratio. The idea is internally consistent, but the confusion arises because the small-scale map is used to portray large-scale features (e.g., the continent) while the large-scale map provides a much more detailed view of small-scale features (such as a county). To avoid confusion between large- and small-scale maps, think of an example map where the scale is 1:1. Although one is a small number, a theoretical map of Kansas at a scale of 1:1 (**large** scale) would be actual size of the state (one mile = one mile) and represent an exceptional **large** map. A safe policy is to be careful and ask for definitions if maps are being explicitly described or discussed in considerations of scale.

2. Scales are human inventions for dividing up and classifying nature, which is continuous. As a result, there is no one "right" classification of scales -- these have to be user-dependent, which requires some level of definition and agreement. They also have inherently "soft" boundaries; a block of land that is a few square miles in area could be considered either 'section-scale' or 'township-scale' -- or both. Although specific applications may require specific definitions, general discussions can use the kind of fuzzy definitions given below for classifying features and processes. Table 1 provides some examples of terms, concepts and values associated with a range of space and time scales. Note that the unit ranges are approximate and that there are gaps and overlaps in the numbers given -- this reflects the "soft boundaries" and common usage; it is a guideline, not a standard.

3.1.2 Spatial scale and variability

In ground water issues important to Kansas, horizontal spatial scales of importance are usually in miles to tens of miles, or perhaps a hundred – while vertical spatial scales, those of soil and aquifer layers and ground water bodies, are measured in feet to hundreds of feet. Nothing is absolutely uniform, but large horizontal features generally tend to vary rather gradually; however, gradual horizontal variations on the scale of the geologic unit can include local changes that are quite abrupt on the scale of the vertical measurements used to determine ground water inventories. To make estimates from relatively few sampling or measurement points over large regions requires the application of the concept of continuity for features like aquifer properties. This is a powerful, economical, and widely used approach, but it puts limits on the confidence of the interpolated values that are far from measurement points. These limits represent the **uncertainty** of the estimate, which is determined largely by the small-scale **variability** of the large-scale feature. In such cases, the uncertainty in the actual measurements (see uncertainty section for discussion of accuracy and precision) is usually minor compared to the uncertainty introduced by variability and problems of representative sampling over a large area.

Quantitative variability -- both spatial and temporal -- has two important components: the magnitude (the total or maximum amount of change) and the frequency (the rate of change per unit distance, area, time, etc.). Driving across a series of speed bumps exemplifies low-magnitude, high frequency elevation change while driving east to west across Kansas is a moderately high-magnitude but very low frequency change in elevation. Continuing to drive west across the continental divide brings an experience that is high-magnitude and moderately high-frequency change. Qualitative variability occurs, but we more commonly express it in quantitative terms -- a change in the nature of the aquifer unit, for example, usually corresponds to a quantitative change in hydraulic conductivity, water quality, or some other measurable characteristic.

Table 3.1: Examples of spatial and temporal scales

Spatial Scales			Temporal Scales		
Unit	**Term**	**Feature example**	**Unit**	**Term**	**Process examples**
<0.5 mi <0.25 mi^2	local, field-scale	Point observations (e.g., wells)	Min-hour	instantaneous	water level measurement
~0.5-5 mi ~0.5-20+ mi^2	section-scale	pumping well zone of influence; measurement densities in well-studied areas	days (~0.5-15)	days	fluctuations in precipitation, pumping, barometric pressure, etc.
~5-10 mi ~20-50 mi^2	township-scale	typical level of generalization supported by statewide data sets	months (~0.5-6)	months (seasonal, intra-annual)	crop and pumping cycles, precipitation patterns, water table recovery
~10-50 mi ~50-300 mi^2	county-scale	Some climatic parameters such as evaporation	years (~0.5-5)	years (annual, inter-annual)	management and regulatory cycles, short-term variability averaging
30-100 mi 300-10,000 mi^2	Regional (e.g. GMD-scale)	Nation-wide, generalized data sets like NRCSSTATSGO soils data	decades (~0.5-2+)	decades	planning, economic cycles, long-term variability averaging
>100 mi >1000 mi^2	Aquifer-scale	Very long-term processes; climatic and geologic time scales	long-term (>~25 yr)	long-term	natural groundwater flow and recharge

In the horizontal dimension, ground water, like surface water, represents a special case because it is a fluid -- which means that it will fill available openings, seek a common surface level under the influence of gravity, and is mobile (that is, will ‘run downhill’). This means that ideally, an undisturbed ground-water surface would be a nearly horizontal plane with a slope determined by the tilt of the land and the local water balance. This is a very powerful and useful model, and water resource assessment and management would be vastly more difficult without it. However, it is not perfectly accurate. Even under natural settings, recharge, discharge, and other physical aquifer characteristics cause variations in water level that can become even greater when large quantities of water are pumped from the system. In the case of water-level measurements, our interpretations have uncertainties caused by variability of the system, but in this case variations over time (**temporal variability**) are likely to be at least as important as spatial variability. These are discussed in the following section.

3.1.3 Temporal scale and variability

Most geologic features can be treated as invariant on human scales -- natural features on the landscape change rapidly only in rare catastrophic events (floods or earthquakes) or by direct and focused human intervention. If we measure the depth to bedrock at points A and B, we can go back and measure points at C, D, and E a week or a year from now with great confidence that A and B will not have changed in the meantime. This gives us the relative luxury of being able to take our time to decide how much information we need about the feature; we can go back and expand our store of knowledge when, where, and how we wish.

By contrast, water features are not so cooperative or accommodating. First and foremost, if we are concerned about trends in a changing system, we cannot "go back" in time to take measurements we later decide that we need (although we can sometimes tease more information out of the measurements we did take). Secondly, ground-water levels in many (but not all!) locations can be somewhat dynamic in response to other factors. For example, ground water level can fluctuate in response to barometric pressure changes (at frequencies of hours to days), and may also respond rapidly to nearby ground-water withdrawals or to major recharge events (floods or major storms). Recovery from perturbation can be much slower -- it takes many months for wells to recover from the irrigation-pumping season, and in some areas they probably never regain full equilibrium before the pumping season starts again. Finally, the natural time constants of ground-water systems are very long by human standards. For example, the best estimates of natural ground-water flow rates (undisturbed by pumping) in the Ogallala aquifer are about one foot per day (with a range of 0.1-10'/day). That means a gallon of water might take 10 years to get from one side of a section of land to another -- but if that gallon and a few million others are pumped out over the course of a few months, changes occur much more rapidly.

For an overview of examples of some of these features, see the instrumental hydrographs from some wells in GMD4 (Figure 4.3 below). This record illustrates barometric fluctuations (very strong in one well, less so in the other) and protracted recovery curves in both. These records are discussed and explained in more detail in section 4 (below) on Uncertainty.

4. Uncertainty

4.1 Types and sources of uncertainty

Uncertainty is a fundamental aspect of all experiential knowledge, and is a central theme of science. Scientific progress occurs through the identification, explanation, and reduction of uncertainty. This seems counter to the popular view of science as the source of confidence and certainty; the apparent paradox is resolved by realizing that many (but far from all!) scientific projects work at reducing uncertainties that are already small compared to issues that the general public worry about.

The words used to describe scientific and technical uncertainty sometimes provoke misunderstanding. In particular, two terms that have moral connotations in ordinary speech are used in a value-neutral way in science. "Error" is a term used to describe certain kinds of uncertainties in a measurement or set of measurements, and "bias" describes the amount and direction of a consistent difference between the measured value and the true value. Although we work to reduce both, neither term indicates failure, negligence, or a bad attitude.

Uncertainty can arise from two sources -- one is the quality (accuracy) of the measurement or observation, and the other is our use or interpretation of the measurement. The second category is far broader, and in most large or complex systems (such as hydrology and water resources) is usually the critical issue. It includes not only interpretation of data, but also the design of experiments and observations -- where, when, and how should we make measurements, and what will they represent? This requires some appreciation of the purpose and uses of the data by those who make the measurements, which in turn requires articulation of the management needs and desires.

In complex systems, uncertainties interact and combine. Scientist and engineers have mathematical formulas for ‘propagation of uncertainty’ from multiple factors, but an important practical point is identification of the limiting uncertainty or uncertainties for the final information product. We often spend considerable time and effort improving techniques that are already much better than the ‘weakest link’ in the process, producing no real gain in the overall quality of information. The discussion in this section focuses on the issue of water-level determination, which is one of the more complex components of understanding the hydrologic system, and which provides excellent examples of most of the points previously discussed.

4.2 Data uncertainties

Uncertainties in actual measured values have a long history of study and definition. A measurement technique is considered accurate if the average value obtained by repeated measurements of the same thing is close to the ‘true’ value (how we evaluate that is beyond the scope of this discussion -- but there are ways, even though we can't exactly know what the true value is). Everybody is familiar, however, with situations where this statistical definition of accuracy seems unhelpful in the individual case:

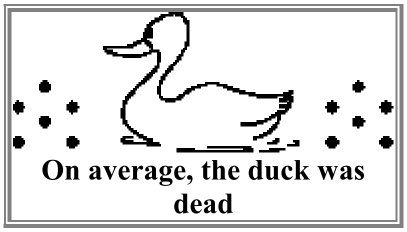

Figure 4.1. The average location of all of the pellets is right on target – but none of the actual locations are.

A further characterization of measurements is in terms of precision as well as accuracy; precision is the degree to which repeated measurements agree with each other, rather than with the "true" value. Precision and accuracy are related, but are not the same:

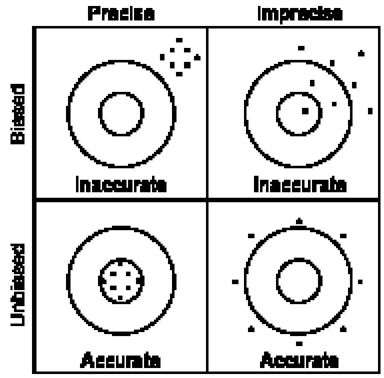

Figure 4.2. The need for both precision and accuracy depends on the scale of the application and the scale of the measurement.

A consistently biased measurement is just as good as an unbiased measurement if it is a **difference** that is being determined. This is important to water-level measurements because the absolute elevation of the well is often only approximately known. The difference between any two measurements made in the same well is not affected by this, however, since any error in absolute elevation is canceled when the difference is taken. All that is required is that the bias be consistent -- and that the measurements continue in the same well.

4.3 Combination and comparison of data with uncertainties

Understanding and estimating the uncertainties of our primary numbers are only part of the process – we always want to look at calculated results (for example, changes), or to compare different measurements across space or time. How do we assess the uncertainties in the calculated values or comparisons?

Standard formulas used in the physical sciences and engineering permit us to evaluate the uncertainty in a sum, difference, product or quotient if we know the uncertainties in the component numbers. An example of applying this approach to the water level differences calculated from a single well over different time periods and with different assumed individual measurement uncertainties is given in Table 4.3. These assume the same decline and the same uncertainty in each year, and solve for the number of years required to generate a water level difference that is at least twice the magnitude of the calculated uncertainty in the difference. For example, suppose that we feel that a given well is being measured under conditions that lead us to assign a value of one foot to the uncertainty in any individual measurement. If that is the case, we will need to take a water level difference over a period of about 6 years in order to measure an actual water table decline of 0.5'/year (or a total of 3 feet in six years) with reasonable accuracy. In this case the result would be a calculated change rate of 0.5 ± 0.23 feet/year.

Table 4.3: Years required for WL decline $\geq$ 2x uncertainty

True decline rate, ft/yr	Annual water level measurement uncertainty, feet				
	0.1	**0.5**	**1.0**	**1.5**	**2.0**
0.1	3	14	28	42	56
0.2	2	7	14	21	28
0.5	**1**	**3**	**6**	**9**	**12**
1.0	1	2	3	5	6
1.5	1	1	2	3	4

An uncertainty of 0.1' is approximately that of the individual measurement, and is unobtainable as a regionally integrated (calculated) result. The value of 0.2' is only marginally less unrealistic, and is included in the table to illustrate the progression of the requirements as a function of the factors considered. Uncertainty values in the range of 0.5-1.0' are probably realistically obtainable by redesign and careful operation and interpretation of an improved measurement network (see section 4.4 and the Appendix 1). With an averaging period of 5-10 years, this would be adequate to determine trends down to the level of about 0.5'/yr, or to about half that minimum at a 10-year period. Under present conditions of water level uncertainty, decade-scale trend analyses are probably adequate for use at the township scale and large and for decline trends in the 0.3-0.4'/year range – which is essentially the same conclusion arrived at in report OFR 2002-25D by examination of mapping and clustering results. Areas with lower rates of change should probably be assessed using alternative criteria. Table 4.3 highlights the uncertainty-trend combinations that would require more than a 10-year observation period.

Note that the above analysis is approximately valid for a spatially distributed network of occasional (e.g., annual) measurements in wells of opportunity, where the measurement wells are unchanged. If water level changes are calculated by direct combination of records from different wells, uncertainties in the ground elevation have to be considered and may greatly expand the overall uncertainty. For different approaches, such as continuous (recorder) measurements of water level, and/or the use of specifically designed or selected index wells, both the assumptions of uncertainty levels and the nature of the analysis would be substantially different.

4.4 A case study of uncertainties – water level measurements

It can be helpful to understand the sources of uncertainties – and how to reduce or work around them – by considering some actual examples. The water level database and measurement program provide a useful case study example; it is the source of our knowledge of, and concerns about aquifer depletion, it is an important source of information for planning and management, and water level observations are subject to a variety of possible influences and interpretations.

Report OFR 2002-25D demonstrated that township- and decade-scale water level trends provide a practical means of regionalizing lifetime estimates, and that for many regions of the Ogallala-High Plains there is a strong relationship between water use data and water level trends. These conclusions about the utility of the data for subunit identification and prioritization are supported by some of the calculation estimates in section 4.3 above.

While supporting the use of existing data for the establishing subunits and considering management options, 2002-25D and the uncertainty considerations also raise questions about needs that may arise for data needed to implement detailed subunit management. It was noted that at the local (subtownship) scale, time periods on the order of 25 years are needed to provide regionally smooth trend maps, and that in some regions, the relationship between use and water level trend was unexpectedly weak. Considering possible sources of uncertainties may help to understand and improve the data base.

An important fundamental question not discussed above is the basic issue of whether the measurements taken represent what is actually expected or intended. The State of Kansas is in a transition period from viewing the aquifer as a whole to taking a much more focused approach to specific areas. The water level measurement program currently in effect (described briefly in section 2.5 of OFR 2002-25G) was designed on the basis of assumptions that the aquifer is uniform and homogeneous, and there is no significant difference in either importance or measurement-related hydrogeology. The results have served well for questions asked in that context, but as more and more attention is focused on the differences rather than the similarities within the aquifer, problems arise.

The annual water-level measurement program has for many years determined water levels during the winter, operating on the assumption that these measurements are reasonably free from interference, provide a reasonable approximation of the recovered equilibrium water table, and can be used to estimate the water remaining in the aquifer. As these assumptions come under closer scrutiny, more detailed measurements are being examined to consider how best to monitor water levels in the future. Two components of these considerations are examined below: the issue of the time and frequency of well measurements, and the question of well interference.

4.4.1 Measurement time and frequency

Two wells in the GMD4 area that have been fitted with downloadable pressure transducers provide information on water level behavior over time scales ranging from minutes to months. In addition, GMD4 staff has made available monthly manual measurements of numerous other wells in the vicinity of the instrumented wells. These are providing valuable information to help understand well monitoring issues.

Figure 4.3 shows plots of the water levels from shortly after the end of irrigation in Fall 2001 to just before the onset of irrigation in Spring 2002; Figure 4.4 shows effects of the onset of irrigation on water levels in the monthly wells.

The curves of figure 4.3 address the assumption of a recovered water table. Annual measurements were made in the first week of January, and both of the recorder wells showed water level rises of about 0.5 feet over the succeeding two months - and do not appear to have been fully leveled off at that point. These observations are supported by the measurements in the monthly wells (http://www.kgs.ukans.edu/HighPlains/GMD4.htm). Water level exhibits continued variability on time scales of months; this creates an uncertainty not in the measured elevation, but in what that measurement represents in terms of the program objective (understanding changes in the equilibrated water table).

One of the wells shown in figure 4.3 has a strong barometric pressure response, with observed water level changes in excess of 0.5 feet on a time scale of a few days. The fitted curve presumably represents the trend line of the water table, and is what measurements should be expected to determine. However, individual measurements (even if repeated at the well head over a few days) can produce values that deviate in either direction from the trend line by >0.5' (while the trend line itself is > 0.5' below the assumed full-recovery water level). This is a level of uncertainty imposed by short-term (high frequency) variations in the condition measured. Again, it is not an uncertainty in the instantaneous measurement value, but in what that represents in terms of the average (in this case over periods of days) water-level response.

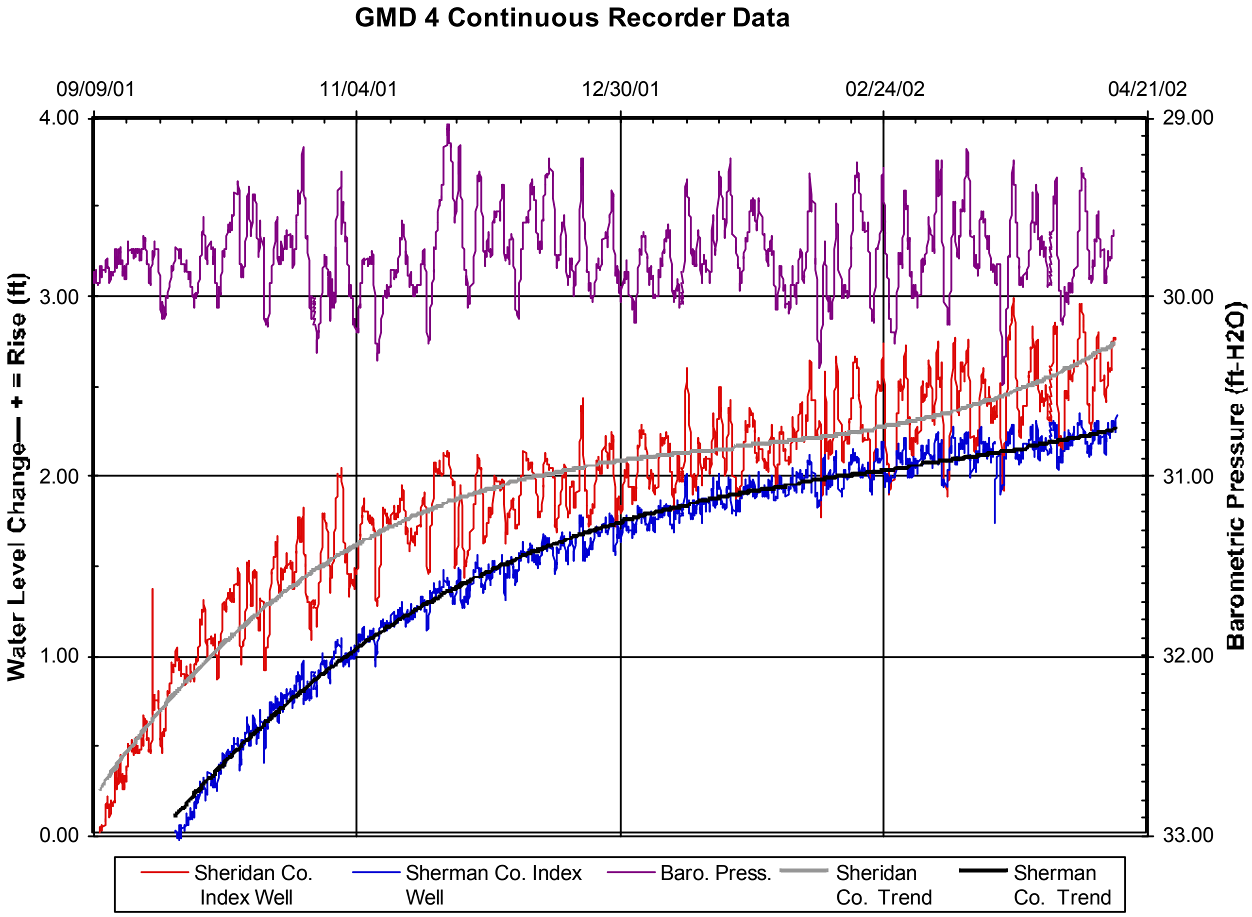

Figure 4.3. Transducer water level measurements at two wells in GMD4 for the recovery period prior to pumping. The middle plot is for a well in eastern Sheridan County, a region of high decline; the lower plot is for a well in western Sherman County, a region with lower decline rates. Also shown are the trend lines averaging the individual recorder measurements and the barometric pressure record from Goodland, Kansas (top plot). See figure 4.4 for the effects of pumping.

At least as significant is the fact that a high barometric efficiency in well water indicates **confined or semi-confined aquifer** behavior. The Ogallala-High Plains aquifer system is generally regarded as an unconfined aquifer system (also known as a phreatic or water table aquifer -- one in which the ground water surface is in pressure equilibrium with the atmosphere). We know that it contains areas where the aquifer is confined or semi-confined, but because the apparent water levels and water level changes in confined systems have different meanings than water table elevations in an unconfined aquifer, observations from the two types of wells of systems should be combined or compared carefully, if at all.

The data in figure 4.4 illustrate the drawdown occurring in wells during the irrigation season that will affect the long-term viability of a given irrigation well in a given area. All wells are operating the same types of center pivots, and most pump at about the same flow rate of approximately 500–600 gpm. These drawdown plots illustrate the points made in OFR 2002-25C, and in section 4.5 of this report (below).

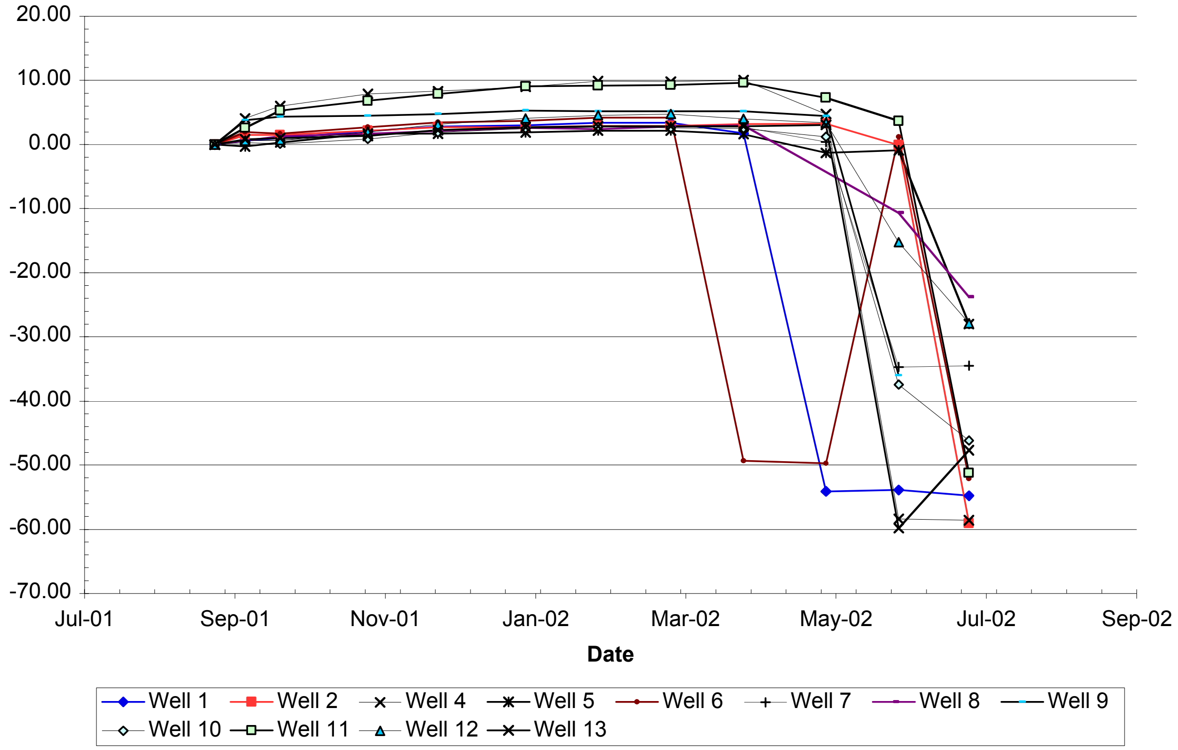

Figure 4.4: Monthly measurements of water level in central GMD4 wells (Sherman-Thomas-Sheridan counties). Note that early in the pumping season drawdowns range from near zero to over 60 feet; four of the wells show prompt initial drawdowns of more than 30 feet.

Almost all monthly wells experienced a significant change in water level between early January (the time of the annual program measurements) and mid-March. The amount of that change was not consistent, ranging from <0.2 to >1.0 feet, but the most common amount of change was in the vicinity of 0.5', as was seen in the recorder wells. The period of late December through early January generally exhibits much higher and more variable (between wells) rates of change than does the (February-March) period, suggesting that measurements later in the winter season will be more consistently representative of the desired condition than the standard early January measurement time.

Several wells show up-and-down responses or breaks in the slope of the recovery curve. These features could be due to either pumping patterns in the measured well, local well interference (nearby pumping), or the effects of having measured successive points at opposite extremes of the barometric response pattern. The latter possibility can be checked by detailed comparison with barometric pressure records; the issue of pumping interferences is discussed in section 4.5 of this report.

It is important to note that the uncertainties discussed in this section can be significantly reduced or eliminated. Testing of wells for barometric response would permit replacement of wells that are locally confined or semi-confined, and identification of larger areas that need to be monitored and managed as a confined aquifer subunit. This would create a more consistent network of water table wells that would provide measurements with less short-term variability and are more representative of the intended aquifer measurements. Moving the measurement period later in the recovery season could significantly reduce the effects of incomplete recovery on intermediate-term variability. Continuous monitoring of more wells would provide the information needed to assess the regional degree of recovery and identify possible anomalies. These and other issues are addressed in an initial set of recommendations for measurement program refinement, presented as Appendix 1 of this report.

4.5 Uncertainties due to human interference.

The uncertainties discussed in the preceding section (barometric responses and recovery from pumping) are natural hydrologic responses, and can be predicted if aquifer characteristics and forcing functions (pumping drawdown and barometric pressure) are known. The preceding section also illustrated the magnitude of the effect of pumping on measured local water levels.

Local well interaction – the response of neighboring wells to water table drawdown from nearby pumping – is another source of uncertainty in well measurements. Although irrigation pumping generally does not occur in the winter, irrigation wells may be pumped for a variety of reasons (system testing and repair, chemigation, ‘pre-irrigation’ soil conditioning, etc.), and there are a substantial number of non-irrigation wells (e.g., municipal and industrial) that are pumped at least occasionally on a year-around basis. Recent pumping in a measured well, or nearby pumping (within a radius of a few miles) of other wells, can affect water levels by a significant amount that will depend on the location, duration, and rate of pumping and the local aquifer characteristics.

Drawdown from pumping wells alters (lowers) the water table in a variable area surrounding the pumped well, depending on the rate and duration of pumping and the aquifer characteristics (especially the Transmissivity, T). Figures 4.5 and 4.6 show plots of the radius of the effects of pumping at two different rates, 250 and 1000 gpm, for a range of transmissivity values. Calculations were made using SuprPump. Additional calculations (not shown) were also made for 50 gpm and 20870 gpm (the highest authorized rate contained in the WIMAS database).

By determining the potential distance range of drawdown effects at the uncertainty threshold of 0.1’ we are able to identify some standard radii of influence for wells, depending on their authorized pumping rate. These radii can be further adjusted if aquifer characteristics are known (see also the OFR 2002-25C report on Yield for discussion of drawdown from the standpoint of local water availability). Figure 4.7 is a map of the locations and sizes of these estimated circular zones of influence, and Table 4.2 summaries the statistics on the absolute and relative areas involved in each of the major groundwater management units.

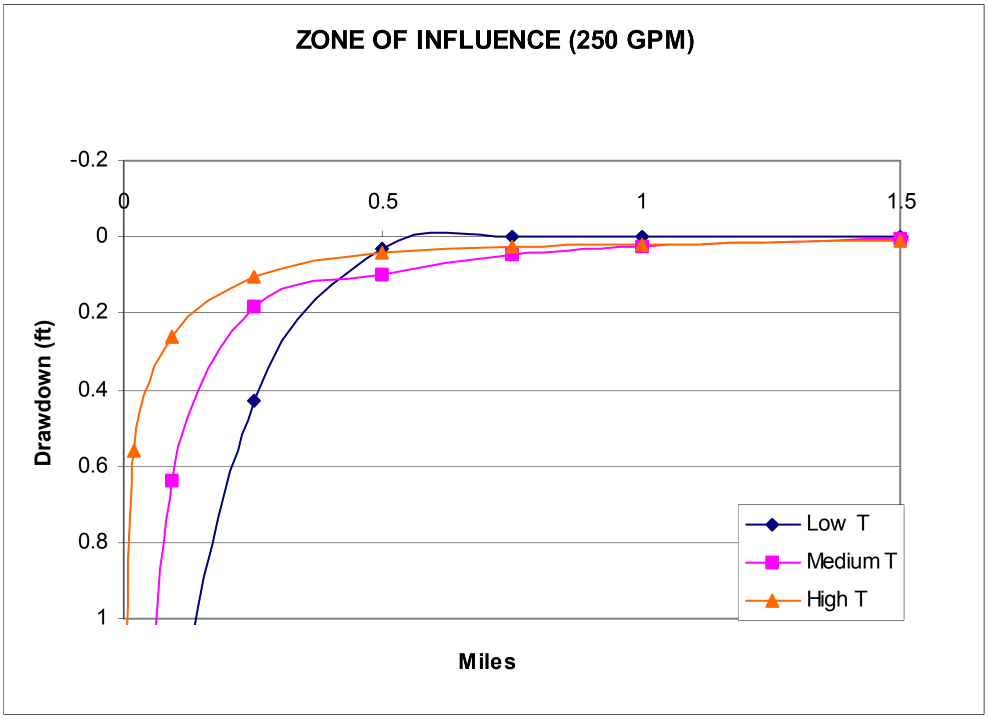

Figure 4.5. Observed drawdown as a function of distance from pumping well for high, low and medium, transmissivity values and a pumping rate of 250 gpm.

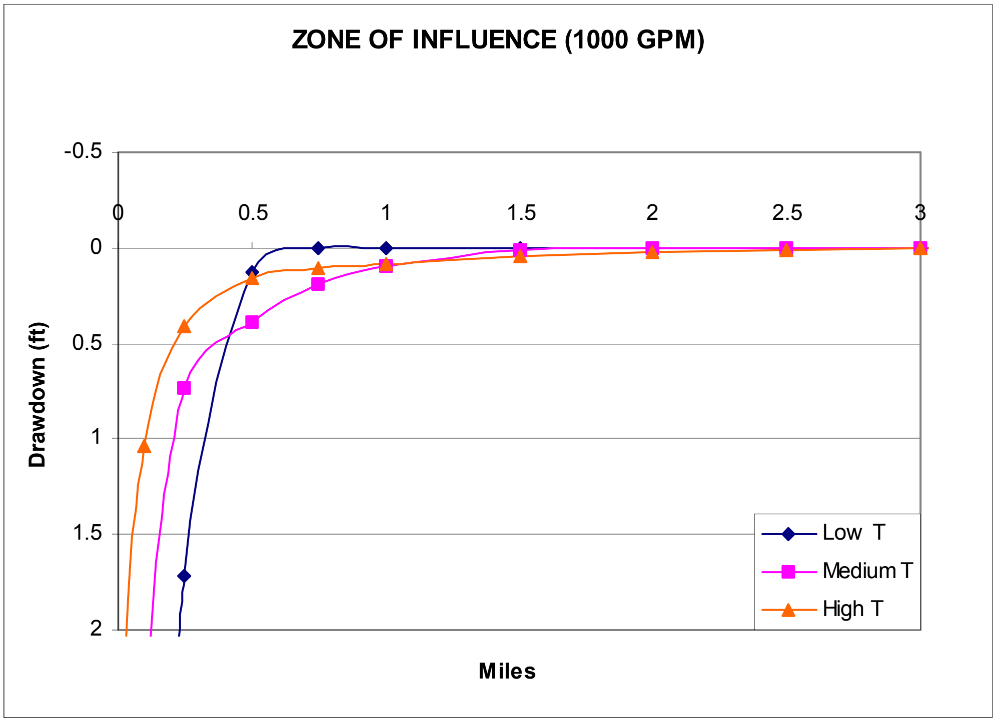

Figure 4.6. Observed drawdown as a function of distance from pumping well for high, low and medium, transmissivity values and a pumping rate of 1000 gpm.

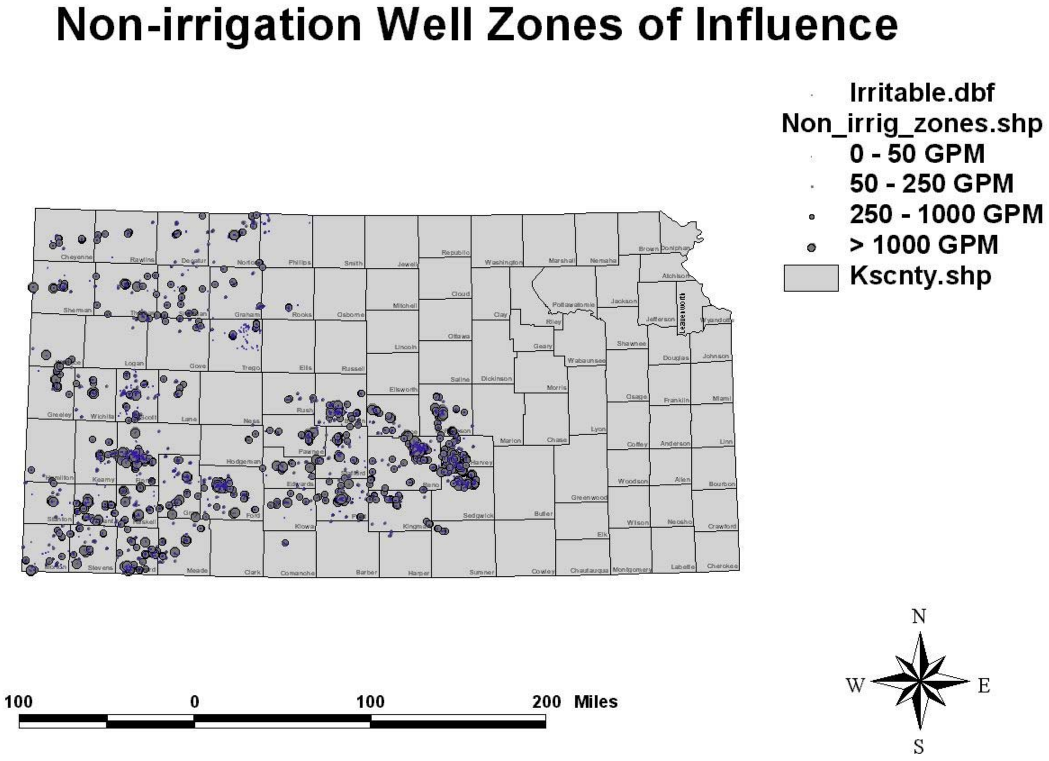

Figure 4.7. Map of non-irrigation water rights in the High Plains aquifer system. Each well is surrounded by a buffer zone, the radius of which is estimated on the basis of authorized pumping rate. See Table 4.2 for the fraction of the total area within the possible zone of influence (ZI) of non-irrigation well.

Table 4.2: Areas potential influenced by non-irrigation wells

Areas associated with non-irrigation well zones of influence (ZI)						
GMD #	**Non-irrigation wells**	**Total GMD area (mi^2)**	**Area inside total ZI (mi^2)**	**Area inside total ZI (mi^2)**	**% Area inside ZI**	**% Area outside ZI**
1	222	1827.44	471.85	1355.59	25.82	74.18
2	534	1369.86	778.67	591.18	56.84	43.16
3	1233	8338.91	2091.96	6246.95	25.09	74.91
4	271	4873.06	654.51	4218.55	13.43	86.57
5	461	3906.76	1132.56	2774.21	28.99	71.01
No GMD	526					
Total	3247	20316.03	5129.55	15186.48	25.25	74.75

An extreme example of interference is illustrated by Figure 4.8, showing the water level measurements from irrigation well (USGS ID number 375540097320901), located in southwestern Harvey County. The maximum difference in repeated water level measurements made during each winter period (December, January and February) was graphed for the years 1959-2000. During 25 of the years, the maximum deviations between measurements taken during the same winter season were less than 6 feet. However, during 16 of the years the deviation between measurements was between 30 and 45 feet. Only one year, 2000, had a measurement between 6 and 30 feet. Thus, the graph reflects two distinct water level ranges. Upon further investigation, it was found that this irrigation well was located within 200 feet of a municipal well belonging to the city of Wichita that has an authorized water right pumping rate of 20870 gallons per minute. It appears that during the sixteen years with the high levels of deviation, at the time a measurement was taken, the municipal well was either actively pumping or had recently been pumping.

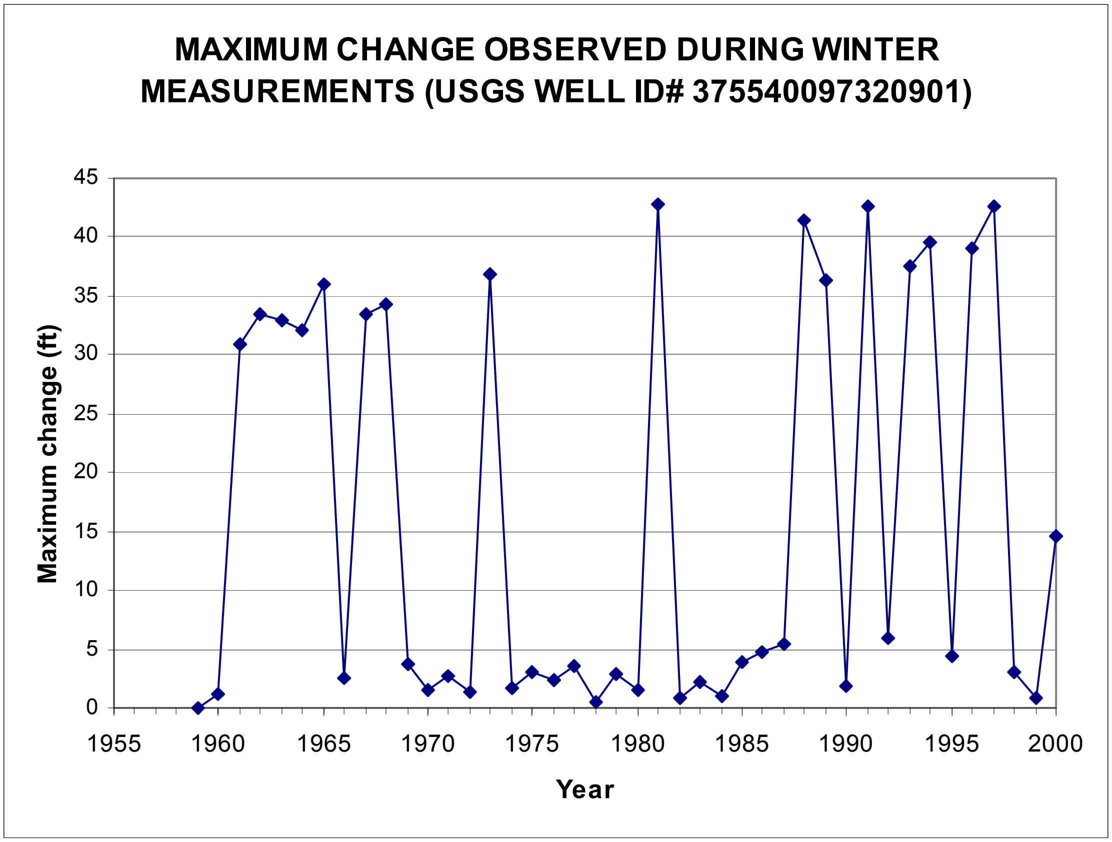

Figure 4.8: Variability of winter water level measurements in well 375540097320901, located in southwestern Harvey County – in close proximity to a high volume municipal supply well.

Contrast the situation shown in Figure 4.8 with that of an irrigation well (USGS ID number 373422098063301) in central Kingman County (Figure 4.9). The maximum difference in water level measurements during each winter period for this well was graphed for the available years 1979-1996. During this time period, the maximum winter measurement water level difference never exceeded one foot. The closest non-irrigation well is a municipal well for the city of Kingman, 2.6 miles away. This municipal well has an authorized pumping rate of only 700 GPM. All other non-irrigation wells are over 3 miles away. Thus, it appears that this relatively isolated irrigation well produces winter water level measurements that are unlikely to be greatly affected by neighbor well interference.

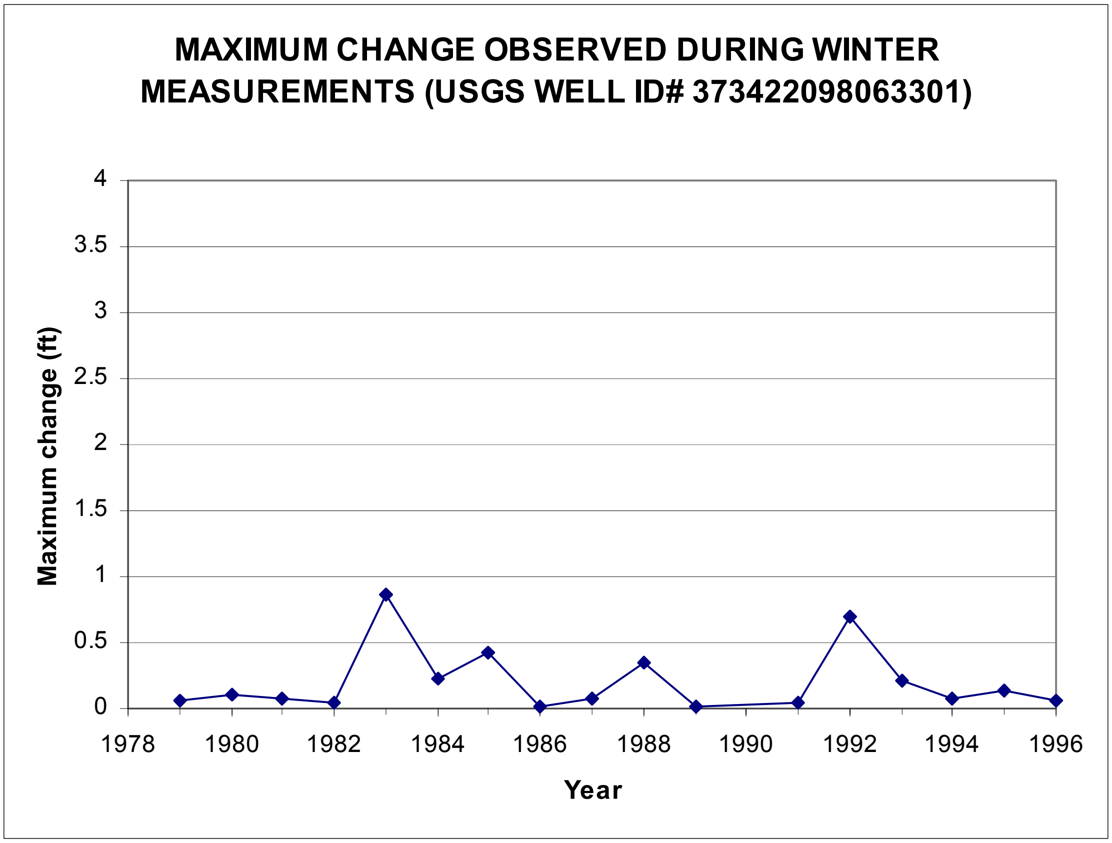

Figure 4.9: Differences in winter water level measurements for a Kingman County irrigation well distant from any significant non-irrigation pumping.

Figure 4.7 illustrates the potential for interference in water level measurements -- and this does not include interference resulting from off-season pumping of irrigation wells or of non-permitted (e.g., domestic) wells. Uncertainties from this source are probabilistic; therefore they cannot be assessed rigorously on a site-specific basis without actual experimental measurements, but sites and measurement times can be selected to minimize the probability of interference (see section 4.5).

5. Data limitations and applications

- A section-based grid system provides the most flexible, recognizable and consistent way of presenting and analyzing data. However, present limitations in some of the databases mean that the appropriate scale of management application is limited to subunits comparable to or larger than a township in size.

- Present water-level trend information is limited in scope to interpretation at the township scale in core regions of the aquifer, and to interpretation of trends over time periods of a decade or longer. Data are adequate for subunit identification and prioritization, but will probably require refinement for detailed management of priority units.
- Depending on the management strategy adopted, priority units may also require additional hydrogeologic aquifer characterization as part of a long-term management plan.

6. Policy and management implications

- The section-centered database provides a means for matching hydrogeologic and management boundaries at the finest scale supported by the data.
- Data and tools can be assessed in terms of their reliability and precision; they are presently adequate for subunit identification, prioritization, and development of initial management options.
- Proposed management strategies need to be evaluated at the level of uncertainty that is known about a particular data source to determine if the uncertainty is at a level that would change the management strategy's goals or objectives
- Refinement of databases and analyses to provide additional support for protocols, evaluations, and management approaches is practical

7. Potential for improved data or applications

- Lithologic and stratigraphic characteristics of the aquifer that do not vary over time can be further assessed and measured as needs and resources dictate to improve the knowledge base for refined local management. Such characterizations include:
    - ♦ Determination of the bedrock surface underlying the aquifer. The primary sources of are information for improving the characterization are water-well logs (WWC-5 records, and older logs in publications and kept by drillers for wells drilled previous to 1975), and geophysical logs from oil and gas well drilling. Additional information could be obtained from observation well drilling at selected sites of special interest.
    - ♦ Interpretation of the lithologic data for the aquifer, based on mathematical processing and knowledge of sedimentary depositional systems, is important for better characterization of the horizontal and vertical distribution, and probably hydraulic connection, of fine-grained, low permeability and coarse-grained, high permeability zones.
- Time-varying measurements, such as water-table elevation, can be refined and improved for specific local areas as illustrated by the results of the case studies and considerations reported in this and the companion OFRs. Among the improvements possible are:
    - ♦ Evaluation and minimization of the potential for pumping interference with water levels in measurement wells.

    - ♦ Establishing criteria for ensuring that measurements represent as nearly as possible the average elevation of the recovered water table, and that probable biases are understood and evaluated (see section 4 and report Appendix).
    - ♦ Determination of whether the water-level measurements represent water-table conditions in an unconfined portion of the aquifer or a potentiometric surface in a confined area (as described in uncertainty subsection 4.4 above).
- Access to and understanding of the available data and information by water users and managers can be improved by expanding the inventory of user-friendly data and tool sources, as discussed in section 2 above.

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Appendix 1. Recommendations for Improving and Adapting the Annual Water Level Measurement Program for Aquifer Subunit Management Requirements

Potential uncertainties (other than the accuracy of the measurement itself, which is usually not the limiting uncertainty) in individual well measurements include:

- Incomplete regional recovery from the stress of the previous pumping season;
- Short-term local variations around the mean water level due to barometric pressure fluctuations;
- Systematic differences in confined and unconfined aquifer water levels (pressure variation suggests confinement); and
- Possible transient or sustained perturbation due to pumping of nearby wells.

In addition, there are other uncertainties that come into play in comparison of water level changes using multiple wells, especially if the records from different wells are combined over time.

The following items represent suggested options for reducing or controlling uncertainties and undesirable effects on applications of the data.

Preliminary draft recommendations, Water level measurement program upgrade (items 1-4 can be implemented under present program arrangements; 5-6 would require reorganization)

1. Ground (datum) elevation surveys (better than 0.5' accuracy) to be made on all replaced/replacement well pairs, from now on, and retrospectively to '95 as resources permit.

Rationale: this is required to make the replacement well a true replacement in terms of water level/difference measurements – without this, well changes may introduce up to several feet of instantaneous offset into the region represented by the well.
Note 1 – this is a cost item, but is critical component of improving absolute accuracy and precision of change measurements.
Note 2 – This is one of the few possibilities for retrospectively improving the quality of measurements in the past decade, where previously measured wells still exist and can be surveyed along with their replacements.

2. Wells to be evaluated for proximity to non-irrigation wells (present and recent past network wells) that might produce winter-season interferences.
Note: this is readily done as a GIS exercise.

3. Develop criteria and priorities for investigating and replacing network wells with high probability of interference, and/or questionable representativeness.

3.1. Wells to be evaluated for barometric pressure response/confined aquifer characteristics.

Note 1: Although this involves some cost and effort, it is fairly easily achieved by rotating movable transducer units through wells (when they are not being pumped) for time periods of a few days to a week.

Note 2: This can and should be prioritized according to the sensitivity/importance of the well data (e.g., classification of subunit and area represented by well)

3.2 Develop criteria and priorities for replacing and/or measuring high variability wells, and for identifying the geographic extent and characteristics of confined or semi-confined aquifer subunits.

4. Shift measurement times to as late in the non-irrigation season as is feasible to maximize recovery.

Note 1: Synoptic measurements are NOT necessary; local variations in (e.g.) cropping or pre-irrigation practices may actually make for more efficient use of personnel and equipment by spreading the measurement period over a longer time.

Note 2: An initial transition period of doing both standard early January and late-season measurements, at least in some regions, might be desirable as cross checks on the effects of the transition – this would be a cost item.

5. Redesign measurement system to conform to and support high priority management subunits – Develop an orderly evolution from the present system that maintains and improves existing data source, into a management-oriented system that includes:

5.1. One or more continuously monitored (non-pumping) index wells per unit

5.2. A network of hand-measured wells (and/or additional recorder wells) with schedule/frequency keyed to index well data and local pumping practices to supplement the existing network.

5.3. Options for including owner-participant contributed measurements into the centralized (Wizard or Wizard-derived) database for easy access and analysis of all available data (possible MOU or other mechanism) – subject to review and quality control

5. Develop more involvement of GMD’s and DWR field offices to maximize local relevance of and participation in the program; retain KGS/DWR design oversight, data storage, data evaluation/interpretation, and data dissemination to maintain credibility and accessibility.

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