Quality-Assurance Plan for Ground-Water Activities in the Kentucky Water Science Center

Compiled by Charles J. Taylor

U.S. Geological Survey Water Resources

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INTRODUCTION

Quality assurance may be defined as any procedure or activity that contributes to the collection of accurate and reliable data. In the context of the mission statement of the Water Resources Division of the U.S. Geological Survey, quality assurance includes the selection and maintenance of equipment, selection and documentation of investigative procedures or methodology, review and interpretation of data, and training of personnel, used to conduct water-resources investigations. This document presents the basic principles and guidelines used by the Kentucky Science Center to assure the technical quality and reliability of data, interpretative reports, and other products obtained during ground-water-related investigations and data-collection activities.

QUALITY-ASSURANCE GUIDELINES

The basic principles used in the Kentucky Science Center in planning and conducting ground-water-related investigations or data-collection activities are summarized as follows:

1. All Science Center personnel who supervise or conduct ground-water investigations and data-collection activities are expected to read and familiarize themselves with the content of OFR 97-11. All technical and scientific activities, whether in the field or in the office, will be performed in accordance with USGS practices and policies specified in Open-File Report 97-11, "A Quality-Assurance Plan for Science Center Ground-Water Activities of the U.S. Geological Survey". A copy of this report is provided as Appendix A.

2. Investigations and data-collection activities will be planned to effectively and efficiently provide the informational needs of the cooperator or support the needs of appropriate local, State, and Federal water-resources programs.

3. Investigations and data-collection activities will be performed by technically proficient personnel performing at a level equal to their training and experience.

4. All ground-water-related proposals, investigations, data, and reports, will receive appropriate and timely review for completeness, reliability, credibility, and conformance to USGS standards by qualified personnel.

5. Appropriate actions will be taken to correct any observed or suspected program or project deficiencies.

The responsibility of implementing this quality-assurance plan rests with every staff member of the Kentucky Science Center involved in ground-water-related project and data-collection activities and with

the Science Center management. The responsibility of updating this plan lies with the Science Center Ground-Water Specialist and will be performed as needed. The ultimate responsibility for quality assurance lies with the Science Center Director working in concert with the other members of the senior management staff.

The intent of the quality-assurance plan for ground-water activities does not differ in any substantial way from similar plans covering the water-quality and surface-water disciplines. However, because of the greater use of multidisciplinary approaches in most ground-water investigations and the limited number of uniform standards and protocols that govern most investigative methods used for ground-water studies, this plan places a greater emphasis on the technical review process and sources of information that can be utilized as resources for those involved in the collection, interpretation, and reporting of ground-water-related data.

Sources of Information

This quality-assurance plan emphasizes the need for sound project design supported by detailed project proposals and work plans; effective use and management of human and other Science Center resources; contributive supervision by the Science Center management; and technical assistance and project overview by the Science Center's Discipline Specialists. It is incumbent on each project chief, hydrologic technician, and other staff members involved in ground-water studies or data collection to identify and use the resources available to aid them in conducting their duties.

The Office of Ground Water (OGW) maintains an Internet web page that contains technical memoranda and other documents that contain information about field and laboratory methods, ground-water flow and solute-transport modeling, geochemistry, statistics, and other pertinent subjects. The OGW homepage can be accessed at http://water.usgs.gov/usgs/ogw .

The Kentucky Science Center maintains a library (room 61) that contains many monographs, journals, USGS publications, and training videos that are useful as reference and study materials. These materials may be checked out for use by Science Center personnel only. By appointment, members of the general public are also allowed to inspect and use the library, but are not allowed to remove library materials from the premises.

The Science Center Specialists for Ground Water, Water Quality, Surface Water, and Water Use are available to assist in the formulation of proposals and work plans, acquisition of specialized equipment, and in data interpretation and presentation. The Specialists are also helpful in identifying and contacting outside expertise from other USGS offices and personnel within the National Research Program. The individuals who currently serve in Science Center Specialist positions and other members of the Science Center staff who serve in special capacities and are available as resources, are listed table 1.

Table 1. Kentucky Science Center Specialists and other staff in advisory positions

Position	Held by
Director	Mark Ayers
Chief, Hydrologic Investigations Section (HIS)	Peter J. Cinotto
Chief, Hydrologic Surveillance Section (HSS)	Michael Griffin
Science Center Ground-Water Specialist	Charles J. Taylor
Science Center Water-Quality Specialist	Angie Crain
Science Center Surface-Water Specialist	Mike Griffin (Acting)
Collateral Duty Safety Officer (CDSO)	Doug Zettwoch
Science Center Water Use Specialist	Aimee Downs
Science Center Training Officer	Paula Faith
Computer Systems Operator/NWIS Database Administrator	Loren Kloft
GWSI Database Administer	Paula Faith
Reports Editor	Bonnie S. Fink

Many of the techniques and procedures that are more commonly applied in ground-water studies are the subject of various technical memoranda and USGS publications. A partial list of some of these is presented in Appendix B. This list is by no means comprehensive, and the other sources of information discussed in the previous paragraphs should be used as needed.

SCIENCE CENTER-SPECIFIC ISSUES

Some activities and issues that are pertinent to the Kentucky Science Center are not specifically addressed by the previously mentioned references and are discussed in the remaining sections of this document. These include:

1. Location and organization of ground-water-related files Science Center

2. Procedures for entering data into the GWSI electronic database

3. Investigations conducted at or near designated hazardous waste sites (Superfund, RCRA, etc.)

4. Field and laboratory procedures used in water-tracing tests with fluorescent dyes

Location and Organization of Ground-Water-Related Files

Information stored and maintained in Science Center files for future retrieval and use include: (1) GWSI coding forms, (2) GWSI site reference maps, and (3) project data files. These are discussed in more detail in the paragraphs that follow.

GWSI Coding Forms (Schedules)

These include well and spring site schedules that are used to code and input information into the NWIS/GWSI electronic database. The procedures that are to be followed in filling out and submitting GWSI schedules for database entry are described in a following section of this document. The schedules are stored in filing cabinets located in the GW files room (room 59). These cabinets are organized by the

index codes for topographic map sheets within Kentucky (fig. 1).

GWSI Site Reference Maps

Prior to 1990, the locations of ground-water observation or sampling sites recorded on well or spring schedules and/or entered in the NWIS/GWSI database were plotted on 7.5-minute topographic map sheets stored in the vertical map file cabinet in the GW file room. After 1990 as the Science Center's computing and GIS capabilities increased, this practice was largely discontinued. These maps now constitute a mostly historical database. The maintenance of these maps is the responsibility of the Science Center Ground-Water Specialist.

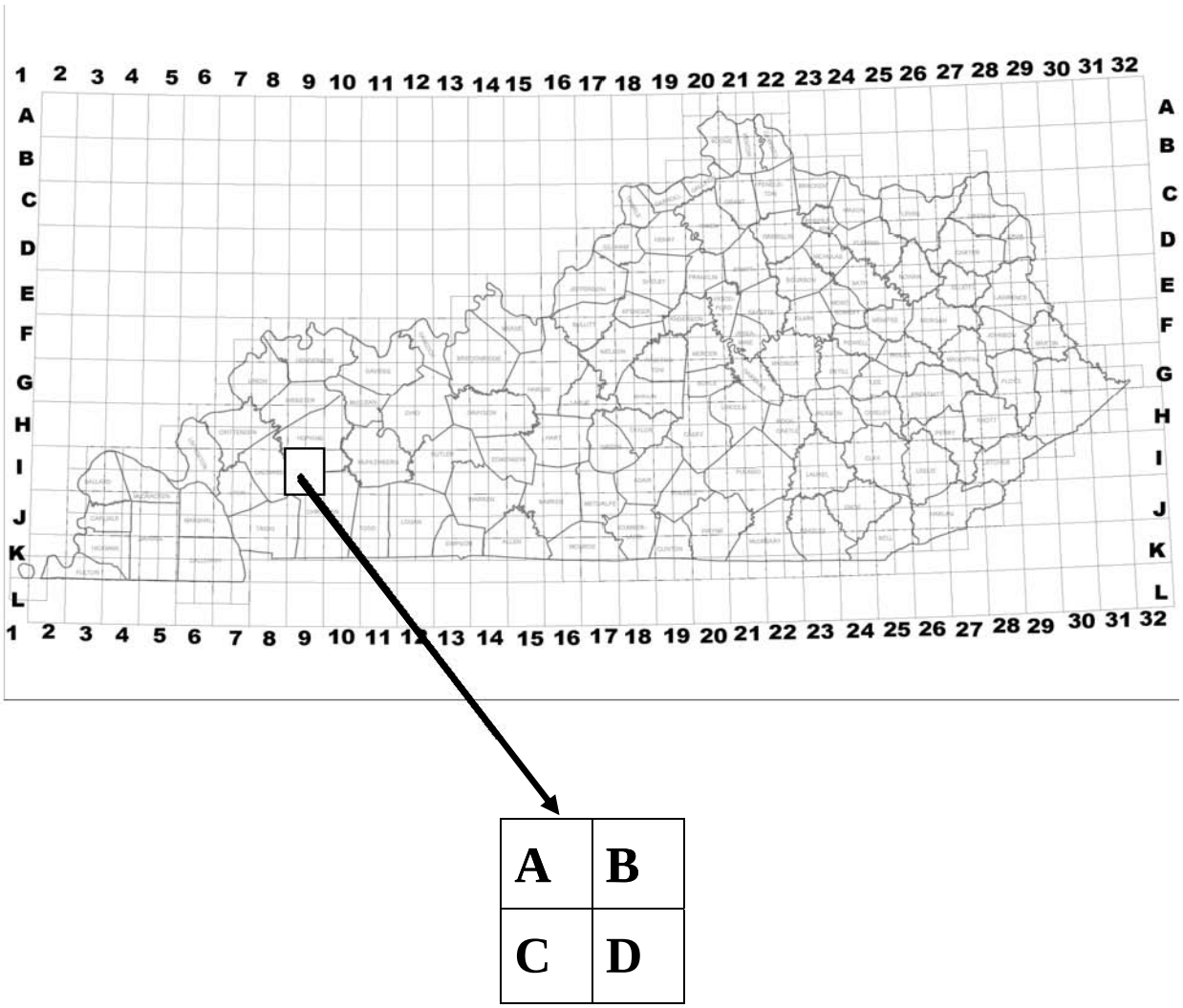

Figure 1. Map showing the grid-numbering/naming system used in the Kentucky Science Center for filing GWSI well and spring schedules. Inset blow-up shows the grid subdivisions, each of which (A-D) corresponds to a 7.5-minute topographic quadrangle map sheet.

Each map sheet is indexed by a topographic sheet code number, and subdivided into four 2x2-minute

sectors (labeled A-D) (fig. 1). Because these maps are used for archival purposes, they should always be returned immediately to the file cabinet after use, and no information appearing on them should be deleted or altered in any way. Plans are being made to develop a GIS library that will allow GWSI users to electronically generate site reference maps at a variety of map scales.

Project Data Files

These files contain original field notes, letters of correspondence (containing data or interpretations), graphs, charts, maps, drawings, laboratory analysis sheets, and other relevant documents related to ground-water investigation projects. Other materials such as photographs, slides, videotapes, and strip charts of various kinds may be included. Project data files are stored in sets in the file cabinets in the GW files room. The sets are arranged (filed) first by county and second by a designated project name. Exceptions are the project data file sets related to the Distler Brickyard Superfund Site, Maxey Flats, the Louisville Alluvial Aquifer, and the Jackson Purchase Hydrologic Atlas series. These sets are stored in separate file cabinets because of the large volume of materials contained in each.

Documents and materials contained in project data file sets are arranged by topical categories as described below. Color-coded file folders are used to speed identification and sorting of the information contained in the documents. The color codes and corresponding topical categories used in this filing system are:

> **Blue—Geologic:** Documents related to stratigraphy, lithology, including geophysical logs, well-construction or borehole logs
> **Green—Miscellaneous:** Miscellaneous or otherwise uncategorized documents, including site maps, letters of correspondence that contain data, and field notebooks
> **Red—Ground-Water Quality:** Documents presenting or interpreting ground-water-quality, geochemical, or isotopic data; also includes various graphical plots (scatter plots, Piper diagrams, etc.)
> **Yellow—Hydrologic:** Documents containing various kinds of ground-water hydrologic data—including hydrographs and aquifer or slug test results

Note that multiple file folders may be present for each of the categories listed above. This is indicated by a letter code ("A, B, C", etc.) located on the top left corner of a folder.

Many paper documents stored in the files were collected prior to development and use of electronic databases and current data-reporting formats. Efforts to sort through, identify, categorize, and properly file these older "historical" materials are ongoing. At present, materials that cannot be correlated or identified with a specific project or investigation are maintained in a set of miscellaneous files stored behind all the other identified (named) project files in each county.

To comply with the Federal procedures for archiving records and documents, all project data file sets are also given a "Permanent" records status and file designation number as follows:

> **1400-23—Miscellaneous Geographic Records (Green folders)**
> **1400-28—Ground-Water Hydrologic Records (Yellow folders)**
> **1400-30—Geologic Records (Blue folders)**
> **1400-40—Water Quality/Geochemical (Red folders)**

The numbers are used for administrative reference only and <u>are not</u> used to organize the files within the cabinets. The "Permanent" records status indicates that the documents are to be permanently archived at the office of origin (i.e. the Kentucky Science Center Office).

Procedures for Entering Project Data into the GWSI Electronic Database

Each project chief is responsible for ensuring that existing electronic data are as complete and accurate as possible and for seeing that collected ground-water data are properly entered onto the NWIS/GWSI database. The Project Chief is responsible for comparing and verifying data contained among field notes, laboratory sheets, NWIS databases, project databases, and reports. Before any investigative project is completed, all collected data must be transferred from field notes, temporary records, etc., to GWSI well or spring schedules, and all applicable data must be entered into the appropriate NWIS database and/or project database. The Project Chief shall inform the Section Chief when the data-entry process has been completed. The Section Chief is responsible for reviewing compliance with these procedures.

New site identification numbers must be provided for any newly drilled and constructed observation wells and for existing wells and springs that have never been sampled. Care must be taken to determine whether any existing well and spring locations are already stored in the GWSI database. Therefore, to avoid duplication or misappropriation of existing GWSI site identification numbers, locations, and names. both paper files and the electronic database should be searched to obtain a list of all existing wells and springs in the study area. The GWSI Database Administrator or Ground-Water Specialist should be consulted in this effort if necessary. Once a list of existing GWSI records has been obtained, the Project Chief should carefully cross-check the site names, location coordinates, and identification numbers, before assigning any new ones. Minimum mandatory data elements required to establish a new site are referenced in table 2.

If a pre-existing site is located which is being or will be used to collect new data, the location coordinates, site name, and site identification number assigned to the site in the GWSI database <u>must be</u> used for all record-keeping, publications, and new data input. If errors or inaccuracies in the existing GWSI records are noted or suspected, the Project Chief should bring these to the attention of the Ground-Water Specialist or Database Administer for a resolution of the problem. This includes any desire by the project chief to change or alter location coordinates or water-level datums (elevations) due to the application of newer, improved, surveying technology (for example, by use of a Global Positioning System survey). If changes/updates are made, these should be noted on the original site schedule and the change dated and initialed by the individual making the change. An entry in the remarks section should be added to the GWSI database and recorded on the paper schedule documenting the change/update.

New sites or existing sites with new data recorded or legacy data changed or updated on the GWSI schedule should be submitted to the Ground-Water Specialist for review and checking. The Ground-Water Specialist will, in turn, give the checked schedules to the GWSI Database Administrator so that the data can be entered into the GWSI database. After data entry, the Database Administrator will file the schedules in the GW files room and print out a report listing all newly entered data for the Project Chief to review.

Table 2. Mandatory site file/web components for the GWSI database

Component number	Description	Mandatory for web display	Mandatory for new site entry for data types	
			SW LK ES ME	GW SP
C004	Source Agency Code	*	*	*
C001	Site ID	*	*	*
C012/C900	Station Name/Local Number	*	*	*
C009	Latitude	*	*	*
C010	Longitude	*	*	*
C011	Latitude/Longitude Accuracy		*	*
C035	Latitude/Longitude Method		*	*
C036	Latitude/Longitude Datum	*	*	*
C006	District Code	*	*	*
C041	Country Code	*	*	*
C007	State Code	*	*	*
C008	County Code	*	*	*
C802	Station Type	*	*	*
C803	Agency Use	*	*	*
C813	Time Zone Code	*	*	*
C814	Daylight Savings Time Flag	*	*	*
C003	Data Reliability	1		*
C002	Site Type	1		*
C023	Use of Site	1,3		*3
Conditionally Mandatory				
C017	Method Altitude Determined	2	2	2
C018	Altitude Accuracy		2	2
C022	Altitude Datum		2	2
C039	National Water Use Code		4	4

[1] Ground-water sites only

[2] Required only if altitude (C016) is entered

[3] Spring does not require "use of site" (C023) entry

[4] Software does not enforce entry for creation of a site, but this field is mandatory to enter water-use data

Investigations Conducted at or near Hazardous Waste Sites

According to USGS policy, appropriate State and Federal health and safety guidelines must be applied to investigations conducted at, or near, hazardous waste sites (fig. 2). For all proposed or new projects, a job-hazard analysis must be prepared and submitted along with the project proposal. In addition, a project work plan and a site-specific safety plan must be prepared and submitted to the CDSO and Regional Safety Officer for review and approval. The work plan and site safety plan may be prepared as two separate documents, or as a single, combined document; however, detailed information about the proposed site investigation work, emergency and first-aid plans, and use of personal protective clothing and equipment must be provided.

Personnel engaged in drilling activities or soil or water-sampling activities at hazardous waste sites that have not been previously sampled and characterized must undergo 40-hour Hazardous Site Worker Training and Certification (renewable annually) and be active participants in an annual Medical Monitoring program. This requirement may be waived for individuals conducting water-level monitoring, water-sampling activities, or other tasks, where it can be demonstrated that no OSHA short-term vapor or contact exposure limits will be exceeded and that vapor and contact exposures will be acceptably minimized and managed by the use of site controls and personal protective equipment. However, before scheduling or proceeding with the use of uncertified personnel, the CDSO and Regional Safety Officer must be consulted and concur.

Drilling, soil sampling, water sampling, and various other investigative activities conducted on behalf of State or Federal environmental regulators at Superfund, RCRA, UST, and other regulated sites, may require the use of protocols and quality-assurance measures specifically approved by the regulatory program. In many instances, these protocols vary considerably from those typically used in "normal" USGS activities—for example, water samples collected for the Superfund program require the use of specialized sample bottle seals and chain-of-custody forms. USEPA guidelines and specified protocols for many investigative activities of the type done by the Kentucky Science Center are described in the following documents (available on-line by searching the website www.epa.gov):

Environmental Investigations Standard Operating Procedures and Quality Assurance Manual, USEPA, Region IV, Environmental Services Division, Athens, Georgia, Sections 1.0-7.11, November 2001

Data Quality Objectives Process for Hazardous Waste Site Investigations, USEPA, Office of Research and Development, Washington, D.C., EPA/600/R-00/007, January 2000

Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water, USEPA Office of Research and Development, Washington, D.C., EPA/600/R-98/128, September 1998

1. INTRODUCTION

A. General Statement

As part of its mission to monitor and to determine the fate and transport of hazardous substances in the water resources of the Nation, the Water Resources Division (WRD) is receiving requests to conduct hydrologic investigations at hazardous waste sites. These include, but are not limited to, sites covered by the Resource Conservation and Recovery Act of 1976 (RCRA); the Hazardous and Solid Waste Amendments (HSWA) to RCRA of 1984; the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 and Superfund Amendments and Reauthorization Act (SARA) of 1986; and the Department of Defense Environmental Contamination Programs (DODEC). **Unless it can be demonstrated that the operation does not involve employee exposure or the reasonable possibility for employee exposure to safety or health hazards, the Occupational Safety and Health Administration (OSHA) regulation 29 CFR 1910.120 and US Environmental Protection Agency (USEPA) regulation 40 CFR 311 apply to such operations.** Additional OSHA and USEPA regulations may apply to specific operations.

Figure 2. Copy of USGS WRD Policy Memorandum 99.03 (Subject: SAFETY--Water Resources Division hazardous waste site operations--Revised Safety Policy and Guidance).

Field and Laboratory Procedures used in Water-Tracing Tests with Fluorescent Dyes

Water-tracing tests using fluorescent dyes are commonly done by personnel in the Kentucky Science Center as part of investigations of karst and fractured rock aquifers. At present, no standards or guidelines have been prepared by the USGS that address practices and techniques for ground-water tracing with dyes; however, a Techniques of Water Resources Investigations (TWRI) Report on this subject is in preparation (Taylor and Greene, *in preparation*). Some valuable, but dated, information about fluorescent dye properties, preparation of dye-concentration standards, and field and laboratory fluorometric analysis methods is contained in a series of TWRI and other reports that discuss the use of dyes in measuring stream discharge and reaeration coefficients (Kilpatrick and Cobb, 1984). Publications that present and discuss examples of ground-water-tracing studies using fluorescent dyes include those of Mull and others (1988); Taylor (1994); Bayless and others, (1994); Taylor and McCombs (1998); Field (1999); and Kuniansky (2001). Much additional literature on this subject is available in various ground-water journals and in conference proceedings published by the National Ground Water Association (NGWA, formerly known as the National Water Well Association, or NWWA) and others (Jones, 1984a, b; NWWA, 1986; NWGA, 1991; and Palmer and others, 1999).

The Kentucky Science Center maintains a dye-tracing laboratory (in the Water-Quality Laboratory, room 27) and separate dye-storage-and-mixing room (room 68, in the warehouse area). Stock dye solutions or powders that are kept on hand for use include: Uranine (Sodium Fluorescein); Rhodamine WT, Eosin, Diphenyl Brilliant Flavine 7GFF (Direct Yellow), and Tinopal CBS-X and 5BM-GX optical brighteners. These dyes have different absorptive, mixing, and other physio-chemical properties, and are not equally suited for use in certain environmental conditions (Smart and Laidlaw, 1977). Please consult with the Ground-Water Specialist prior to using any of these dyes for water-tracing tests.

The laboratory is equipped with a Shimadzu RF-5000 scanning and recording spectrofluoro-photometer. The instrument is operated and maintained according to the manufacturer's detailed instructions, provided in a manual kept in the laboratory. The instrument is used to analyze water and elutant samples (obtained by the chemical processing of charcoal dye detectors) collected for qualitative or quantitative water-tracing tests. The instrument can detect multiple dyes present in a single sample using the excitation and emission wavelength characteristics of individual dyes (table 3). Techniques used in synchronous scanning, a method that is particularly useful for determining the presence or absence of multiple tracer dyes, are described in a paper by Duley (1986). Concentrations of detected tracer dyes can be quantitatively determined to a high precision using calibration curves obtained from analysis of dye-concentration standards prepared freshly in the laboratory using serial dilution techniques (Wilson and others, 1986). Instrument analytical settings and specific calibration techniques vary depending on the type of analysis to be performed. Please consult with the Ground-Water Specialist regarding the methods of operation prior to the use of the instrument.

The Science Center also has two Turner Model 10 filter fluorometers—one equipped with a filter set suitable for the detection of Rhodamine WT dye and one equipped for detection of Sodium Fluorescein. These instruments are usually used only where field detection of dyes is desirable, such as for monitoring during stream discharge or reaeration studies. Higher levels of analytical precision and accuracy are obtained using the scanning and recording spectrofluorophotometer. Calibration of these instruments for either qualitative or quantitative tracing tests is done using dye-concentration standards prepared in the manner stated above. The manufacturer's instruction manuals for these instruments are kept in a file by the Science Center Ground-Water Specialist.

Table 3. Fluorescent properties of tracer dyes used by the Kentucky Science Center Office (modified from Field, 1999, table 2)

Dye name	Color index	CAS no.	Maximum excitation wavelength (nm)	Maximum emission wavelength (nm)	Detection limit in water (ug L^{-1})
Uranine (Sodium Fluorescein)	Acid Yellow 73	518-47-8	492	513	0.002
Rhodamine WT	Acid Red 388	37299-86-8	558	583	0.006
Eosin	Acid Red 87	17372-87-1	515	535	0.01
Diphenyl Brilliant Flavine 7GFF	Direct Yellow 96	61725-08-4	415	489	--
Tinopal CBS-X	Fluorescent Brightener 351	54351-85-8	355	435	0.01
Tinopal 5BM-GX	Fluorescent Brightener 22	12224-01-0	355	435	0.01

The use of fluorescent dyes for water-tracing studies is not regulated in Kentucky. However, prior notification of plans to initiate any dye injection is encouraged by the Kentucky Division of Water. This serves to alert the Division that dyes might be discharging at visible concentrations in Kentucky waterways and provides information that can be used to handle any concerns from private citizens should dye temporarily discolor or affect the quality of water wells or springs. In addition, the State can notify the investigator of other water-tracing tests being conducted in the area, thus preventing interferences between two or more investigators using the same dyes.

All fluorescent dyes used by the Kentucky Science Center have low-moderate toxicity with respect to aquatic organisms and are non-toxic to humans (Smart and Laidlaw, 1977). Water Resources Division Memorandum No. 66.90 (dated May 16, 1966) states that with regard to rhodamine dye, it is the policy of the USGS to attempt in every way practicable to ensure that dye concentrations in water will be maintained at less than 10 micrograms/liter at any water intake which is used to provide water for human consumption. This policy is reaffirmed in Water Resources Division Memorandum No. 85.82, dated April 2, 1985. These policy memoranda were generated in response to concerns about the toxicity of rhodamine B dye—which is no longer used by most practitioners—and the possible generation of diethylnitrosamine, an EPA-designated carcinogen, by the reaction of rhodamine WT with nitrite-rich water. A more recent study indicates that this reaction does not likely occur under most natural conditions (Steinheimer and Johnson, 1986). Nevertheless, the USGS policy regarding the use of rhodamine dyes in tracer tests where a public or private drinking-water supply may be affected remains in force.

An attachment to WRD Memorandum No. 66.90 describes dose computation techniques for fluorescent dyes used in surface-water-tracing studies. However, these techniques are difficult to apply to ground-water studies as there are greater uncertainties with regard to subsurface flow velocities and gradients, dye losses by absorption to the aquifer media, and the distances to downstream dye receptors or resurgence points. Indeed, the objectives of most ground-water-tracing tests are to obtain data to determine these very characteristics. Nevertheless, in keeping with the intent of the policy memoranda, investigators should do everything possible to minimize the amount of dyes used in ground-water-

tracing studies and to ensure that objectionable concentrations of tracer dyes are not reached in water-supply wells or springs. The paper by Field and others (1995) presents a good discussion of these issues and also contains a summary and assessment of the most recent dye toxicity data.

No provisions currently exist for entering water-tracing test data into the NWIS and GWSI databases. In the Kentucky Science Center, standards for reporting dye-tracing test data and plans for archival storage of data are presently under development. Special paper forms have been used in the last several years to help plan and track the analytical results obtained for dye-tracing tests. A new data tracking and archival method is being developed using Microsoft Excel© and a specially formatted spreadsheet template (fig. 3).

Alabama_KeyCave_tracer_test [Shared]

	A	B	C	D	E	F	G	H	I	J
1	U.S. GEOLOGICAL SURVEY- KENTUCKY DISTRICT- DYE-TRACER-TEST REPORT									
2	Tracer Test No.	AL-KEY-I-01	Date of Injection:		1/10/2001					
3			Location of Injection:		Abramson well					
4										
5	Tracer:	Rhodamine WT								
6	Color Index:	Acid Red 388	Explanation of Abbreviations:			N, No tracer detected; P, Positive tracer detection;				
7	Quantity:	7.5 pounds (3 liters)				--, Detector not recovered; R, Lost or not installed.				
8						(B), detector for background fluorescence only				
9			Date of Detector Collection:							
10	Detector I.D.	Site Name								
11	Number		########	12/8/2000	1/8/2001	1/9/2001	1/11/2001	1/12/2001	1/17/2001	1/18/2001
12										
13	AL-KEY-06	Ram Spring		N(B)	N(B)	--	N	--	N	--
14	AL-KEY-16	Rock Church well			N(B)	--	N	--	N	--
15	AL-KEY-19	Oneal Spring #1		N(B)	N(B)	--	N	--	N	--
16	AL-KEY-20	Oneal Spring #2			N(B)	--	--	--	N	--
17	AL-KEY-24	Dust Cave Spring		N(B)	N(B)	--	--	N	N	--
18	AL-KEY-27	Oneal Farm			N(B)	R	R	R	R	R
19	AL-KEY-42	spring		N(B)	N(B)	--	--	N	N	--
20	AL-KEY-45	spring			N(B)	--	--	N	N	--
21	AL-KEY-46	spring		N(B)	N(B)	--	--	N	N	--
22	AL-KEY-67	Cypress Creek @ Hwy 20	N(B)	N(B)	N(B)	--	N	--	P	--
23	AL-KEY-68	Cypress Creek @ C.R.14	N(B)	N(B)	N(B)	--	N	--	N	--
24	AL-KEY-69	Cypress Creek @ Hwy 33	N(B)	N(B)	N(B)	--	N	R	R	R
25	AL-KEY-72	Key Spring		N(B)	N(B)	--	--	N	--	N
26	AL-KEY-73	Fish Camp Spring		N(B)	N(B)	--	--	N	--	N
27	AL-KEY-74	Cypress Knee Spring		N(B)	N(B)	--	--	N	N	--
28	AL-KEY-77	Walker well				N(B)	--	N	--	N
29	AL-KEY-80	Collier Cave north			N(B)	--	--	N	--	N
30	AL-KEY-82	Key Cave west			N(B)	--	--	N	--	N
31	AL-KEY-83	Key Cave east				--	--	N	--	N
32	AL-KEY-90	Oneal old house well				--	N	--	N	--
33	AL-KEY-92	Oneal Office			N(B)	--	--	--	--	N

rhodamine WT (1 of 3) / rhodamine WT (2 of 3) / rhodamine WT (3 of 3) / eosine

Figure 3. Example of Microsoft Excel© spreadsheet template presently being used to report dye-tracing test data.

Dye-Tracing Test References

References cited in the preceding sections are listed here for the reader's convenience:

Bayless, E.R., Taylor, C.J., and Hopkins, M.S., 1994, Directions of ground-water flow and locations of ground-water divides in the Lost River Watershed near Orleans, Indiana: U.S. Geological Survey Water-Resources Investigations Report 94-4195, 25 p.

Duley, J.W., 1986, Water tracing using a scanning spectrofluorometer for detection of fluorescent dyes: *in* Proceedings of the Environmental Problems in Karst Terranes and Their Solutions Conference, Bowling Green, Kentucky, October 28-30, 1986, p. 389-406.

Field, M.S., Wilhelm, R.G., Quinlan, J.F., and Aley, T.J., 1995. An assessment of the potential adverse properties of fluorescent tracer dyes used for groundwater tracing: Environmental Monitoring and Assessment, v. 38, p. 75-96.

Field, M.S., 1999. The QTRACER program for tracer-breakthough curve analysis for karst and fractured-rock aquifers: U.S. Environmental Protection Agency, Atlanta, Georgia, EPA/600/R-98/156a, 137 p.

Jones, W.K., 1984a. Dye tracer tests in karst areas: National Speleological Bulletin, v. 46, p. 3-9.

_____ 1984b, Analysis and interpretation of data from tracer tests in karst areas: National Speleological Bulletin, v. 46, p. 41-47.

Kilpatrick, F.A., and Cobb, E.D., 1985, Measurement of discharge using tracers: U.S. Geological Survey, Techniques of Water-Resources Investigations, Book 3, Chapter A16, 52 p.

Kuniansky, E.L., ed., 2001. U.S. Geological Survey Karst Interest Group Proceedings, St. Petersburg, Florida, February 13-16, 2001: U.S. Geological Survey Water-Resources Investigations Report 01-4011, 211 p.

Mull, D.S., Liebermann, T.D., Smoot, J.L., and Woosley, Jr., L.H., 1988, Application of dye-tracing techniques for determining solute-transport characteristics of ground water in karst terranes: U.S. Environmental Protection Agency, Atlanta, Georgia, EPA 904/6-88-001, 103 p.

NWWA, 1986, Proceedings of the Environmental Problems in Karst Terranes and Their Solutions Conference, October 28-30, 1986, Bowling Green, Kentucky: National Water Well Association, Dublin, Ohio, 525 p.

NWGA, 1991, Proceedings of the Third Conference on Hydrogeology, Ecology, Monitoring, and Management of Ground Water in Karst Terranes, December 4-6, 1991, Maxwell House/Clarion, Nashville, Tennessee: National Ground Water Association, Dublin, Ohio, 793 p.

Palmer, A.N., Palmer, M.V., and Sasowsky, I.D., 1999, Karst modeling: Proceedings of the Symposium held February 24-27, 1999, Charlottesville, Virginia: Karst Waters Institute Special Publication 5, 265 p.

Steinheimer, T.R., and Johnson, S.M., 1986, Investigation of the possible formation of diethylnitrosamine resulting from the use of rhodamine WT as a tracer in river waters: U.S. Geological Survey Water-Supply Paper 2290, p. 37-49.

Smart P.L., and Laidlaw, I.M.S., 1977, An evaluation of some fluorescent dyes used for water tracing: Water Resources Research, v. 13, p. 15-33.

Taylor, C.J., 1994, Summary and interpretation of dye-tracer tests to investigate the hydraulic connection of fractures at a ridge-and-valley-wall site, near Fishtrap Lake, Pike County, Kentucky: U.S. Geological Survey Water Resources Investigations Report, 94-4189, 83 p.

_____ and McCombs, G.K., 1998, Recharge-area delineation and hydrology, McCraken Springs, Fort Knox Military Reservation, Meade County, Kentucky: U.S. Geological Survey Water-Resources Investigations Report 98-4196.

_____ and Greene, E.A., *in preparation*, Use of water-tracing tests, and other quantitative methods, to investigate hydrologic fluxes in karst terranes: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 2, Chapter X4.

Wilson, J.F., Cobb, E.D., and Kilpatrick, F.A., 1986, Fluorometric procedures for dye tracing: U.S. Geological Survey, Techniques of Water-Resources Investigations, Book 3, Chapter A12, 34 p. [Revision of 1968 edition].

APPENDIX A

A QUALITY-ASSURANCE PLAN FOR DISTRICT GROUND-WATER ACTIVITIES OF THE U.S. GEOLOGICAL SURVEY

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U.S. GEOLOGICAL SURVEY

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U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

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ABSTRACT

As the Nation's principal earth-science information agency, the U.S. Geological Survey (USGS) is depended upon to collect data of the highest quality. This document provides the framework for collecting, analyzing and reporting ground-water data that are quality assured and quality controlled.

INTRODUCTION

The Water Resources Division (WRD) of the U.S. Geological Survey (USGS) performs a wide variety of ground-water data-collection programs and investigations to assess the status of the Nation's ground-water resources. Results of these activities are used to aid the Nation in developing, managing, and maintaining its ground-water resources.

As the Nation's principal earth-science information agency, the USGS is depended upon to collect accurate data and produce factual and impartial interpretive reports. Methods for data collection and analysis that were developed by the USGS have become standard techniques used by numerous Federal, State, and local agencies and by private enterprises. Data collected by scientific organizations such as the USGS are being used increasingly by the public to define and examine a variety of natural-resource and environmental problems. Many of these problems are addressed through an open, public process. As a result, scientific organizations are being challenged to demonstrate the credibility of their data on the basis of objective evidence rather than on the organization's history and reputation.

To address these demands and expectations, the WRD has implemented a program designed to ensure that all scientific work done by or for the WRD is conducted in accordance with a quality-assurance (QA) program. The Office of Ground Water (OGW), in coordination with the Branch of Technical Development and Quality Systems, has the responsibility to develop, coordinate, and implement the quality-assurance program for Science Center ground-water activities. As part of that program, the OGW has directed the preparation of a Ground-Water Quality-Assurance Plan (GWQAP) which covers all ground-water activities by Science Center offices of the USGS. USGS Open-File Reports (OFR) 92-136 (Schroder and Shampine, 1992) and 92-162 (Shampine and others, 1992) outline the guidelines for preparing Science Center quality-assurance plans and integrating the quality assurance into project work plans. Guidelines presented here are intended to supplement these two reports and provide more specific details related to ground-water activities.

A quality-assurance plan (QAP) can be defined as a formal document that describes the management policies, objectives, principles, organizational authority, responsibilities, accountability, and implementation plan of a responsible organizational unit or group for ensuring quality in its products. The implementation of a GWQAP will enhance ground-water data collected by the USGS by providing for the following:

- Consistency (across projects, subdistricts, WRD, and so forth);
- Accountability (to client, scientific community, and regulatory agencies);
- Comparability (yields results of known quality);
- Traceability (written record of how, who, and when work was performed, training, equipment, etc.);
- Repeatability (documentation of technique that leads to the similar results time after time with the same accuracy).

This report is a quality-assurance plan for ground-water activities conducted by the USGS and is meant to complement quality-assurance plans for surface-water and water-quality activities and similar plans for Science Center and general project activities throughout the USGS.

The purpose of this GWQAP is to establish a minimum set of guidelines and practices to be used by Science Centers to assure quality in ground-water activities. Included within these practices are the assignment of responsibilities for implementing quality-assurance activities in the Science Center and establishment of review procedures needed to ensure the technical quality and reliability of the ground-water products.

This report presents quality-assurance policies pertaining to the collection, processing, analysis, storage, review, and publication of ground-water data. In addition, policies related to organizational responsibilities, training, and project planning are presented. These policies and practices pertain to all ground-water activities conducted by or for the Science Center offices of the USGS. Ground-water activities include all tasks pertaining to data-collection programs, interpretive and research projects, and data management.

ORGANIZATION AND RESPONSIBILITIES

Though quality assurance is a personal responsibility of all employees of the USGS, ultimate quality-assurance responsibility within each Science Center lies with the Science Center Director. Clear statements of specific responsibilities promote an understanding of each person's role in the overall process of assuring quality and can help to prevent errors and deficiencies that may otherwise occur. Implementation and follow-up responsibilities lie with data-collection staff, project chiefs, section chiefs, discipline specialists, Science Center Directors, regional specialists, and others. Even if quality-assurance responsibilities are ancillary duties for some employees, these functions are to be documented.

The following is a list of specific responsibilities of Science Center personnel for implementing the GWQAP for ground-water activities.

The Science Center Director is responsible for:

- Managing and directing the Science Center program, including all ground-water activities.
- Ensuring that ground-water activities in the Science Center meet the needs of cooperating agencies, including state and local agencies; the general public; and the Federal Government.
- Ensuring that all aspects of this GWQAP are understood and followed by Science Center personnel.
- Providing final resolution of any conflicts or disputes related to ground-water activities within the Science Center.
- Keeping Science Center staff briefed on procedural and technical communications from Region and Headquarters.
- Ensuring that technical reviews of all ground-water activities are conducted.
- Ensuring that all publications and other technical communications released by the Science Center are accurate and are in accord with USGS policy.
- Ensuring that ground-water training is incorporated into each employee' training plan, where appropriate.

The section chief is responsible for:

- Managing and directing ground-water activities assigned to the section and ensuring that the stated objectives are met in a timely manner.
- Reviewing the work plans for ground-water programs and projects.
- Providing the project chief with technical and administrative support as needed.
- Creating, with ground-water personnel in the section, a training plan for each employee, where appropriate.
- Reviewing ground-water reports under his or her direction.
- Monitoring progress of ground-water project chiefs in implementing the GWQAP for their respective projects.

The ground-water project chief is responsible for:

- Directing and conducting the technical work of the project, including all phases of data collection, data review, data storage, data analysis, and report preparation according to appropriate procedures.
- Communicating project plans, progress, and problems to supervisors by providing written progress reports at periodic reviews.
- Preparing written work plans, documenting project activities, and ensuring that data are placed in the USGS National Water Information System (NWIS) data base, as appropriate, prior to project termination.
- Maintaining a project file containing memoranda, personal communications, technical-procedure documents used, original data, and other documentation.
- Ensuring that project activities are carried out in a timely manner.
- Creating, with the supervisor, a personal training plan.
- Archiving of project files, at the completion of the project.

Some of the duties of the Science Center ground-water specialist may be delegated to other personnel. For the remainder of this report, “Science Center ground-water specialist” will refer to these individuals. The Science Center shall appoint a ground-water specialist whose duties shall include but not be limited to:

- Maintaining current ground-water technical expertise for the Science Center.
- Maintaining the ground-water technical-procedure documents file.
- Consulting with the Science Center staff on ground-water technical matters.
- Advising on training needs for employees engaged in ground-water activities.
- Participating in technical reviews of ground-water activities.
- Reviewing ground-water related project proposals.
- Reviewing ground-water related project reports.

TRAINING

Employee training is an investment that has short-term and long-term benefits to Science Center ground-water activities. The immediate benefits permit confidence that the work is being performed correctly and accurately. The long-term benefits provide for technically competent employees that are of great value to the organization. Because all work in the scientific arena is receiving increased scrutiny, the qualifications of ground-water personnel relative to the technical demands of the work to be performed must be well-documented. Training already received as well as current and planned training need to be incorporated into a documented training plan for each employee. Periodic reviews of these plans by Science Center management will help determine additional training needs.

The following quality-assurance activities shall be performed by the Science Center:

1. A written, reviewed, and approved training plan shall be prepared for each employee (including observers and volunteers, as appropriate) performing technical tasks relating to ground water.

    a. Each training plan shall include an individual’s short-term training needs, such as the knowledge and skills needed to perform currently assigned tasks as well as long-term training needs, such as skills needed to perform future tasks and for career development.

    b. Training plans should be reviewed and updated at least annually.

2. Individuals shall receive appropriate training before assigned tasks are performed. Appropriate training includes new employee training, USGS National Training Center courses, mentoring, on-the-job training (OJT), vendor-provided training, and academic courses.

3. Each training activity shall be documented according to existing policy. The Science Center shall establish a training file to facilitate cross referencing by critical task and individual training. Qualifications of contractors performing tasks shall be documented. Qualifications of cooperators (Federal, State, and local agencies) performing tasks shall be to the satisfaction of the Science Center Director.

PLANNING

Science Centers routinely conduct technical ground-water projects and data-collection programs.The success of these activities is dependent on a careful, deliberate, and systematic planning process. Quality-assurance requirements should be integrated into the project proposal, if one is required for the ground-water activity. Whether a ground-water program or project requires a separate quality-assurance plan should be evaluated on the basis of the complexity of the work, the needs of the Science Center or cooperator, or other criteria as described by Shampine and others (1992).

A workplan shall be developed for every ground-water program or project. The workplan can be a part of the proposal or a stand-alone document. The complexity of the program or project will determine the detail of the workplan. The project proposal may satisfy the requirement of a workplan where ground-water activities are routine or highly standardized. The workplan shall include, as appropriate, data-collection and storage plans, equipment and instrumentation needs, data-analysis techniques, report plans, cost estimates, time schedules, availability of personnel, training needs, and other elements, as necessary. Without appropriate project planning (Green, 1991) and the documentation of individual project tasks, quality objectives and project deadlines may not be reasonably known. Initial project/program planning can be guided by a detailed workplan, continued planning can be guided by periodic reviews.

Workplans

To quality assure workplans, the following steps shall be performed by the Science Center:

1. Workplans for programs with ground-water activities should clearly state that the GWQAP will be implemented.

2. To the extent practicable, workplans should state data-quality objectives and describe the strategies to collect data to meet the intended use. When developing data-quality objectives, broader network needs should be considered as well as immediate objectives.

Data-Quality Objectives are those qualitative and quantitative statements developed by data users to specify the quality of data needed from a particular data-collection activity. For example, in order to describe land subsidence in an area, ground-water levels need to be measured using a particular method, at a particular frequency, and to a particular accuracy.

3. The workplan shall specify the means for cataloging and archiving all ground-water activities and files according to WRD policy (Hubbard, 1992).

Development of workplans might also include the following:

1. A bibliographic search of available reports, articles, data, and other pertinent information.

2. Retrieval of relevant data from existing data bases in order to determine the availability of and the need for additional data. Errors or inconsistencies in the data base should be identified and corrected at this time.

3. Review of other USGS file (paper) data, such as field canvass sheets, water-level records, geophysical logs, lithologic logs, water-quality laboratory analytical sheets, or other original data.

Project Reviews

Project reviews are conducted periodically by Science Center management, technical advisors, or discipline specialists to ensure that project objectives are being met and to evaluate implementation of the GWQAP. Project reviews are used to maintain consistency in data collection, data analysis, and reporting. The following quality-assurance functions related to project reviews shall be performed by the Science Center:

1. The Science Center shall establish and implement a ground-water program and project review schedule that considers the technical development and progress of the endeavor. The Science Center shall schedule regular, periodic reviews such as quarterly reviews, or at the 10-, 40-, and 70-percent (10/40/70) milestones of the project. Regularly planned reviews shall ensure that the ground-water program or project is implemented and performed in a manner that results in a quality product done efficiently.

The 10/40/70 review process has been used by numerous Science Centers successfully. In general, the 10-percent review ensures that the project begins properly, that no major technical item is overlooked in the planning, and that the objectives can be accomplished with the proposed approach. The 10-percent review is scheduled after initial reconnaissance, bibliographic and data-base searches, and before any systematic data collection. A topical outline and initial report writing are begun at this early stage. An annotated report outline, including draft illustrations, and a base map typically should be completed at this stage. At the 40-percent review, data collection is well underway, preliminary conclusions made, and any problems in achieving project objectives should be identified. The 40-percent review shall confirm that all the tasks are on track to meet the planned objectives. The purpose of the 70-percent review is to ensure that all the data required to meet the objectives have been obtained, that the data-analysis process is on schedule and is yielding expected or reasonable results, and that the report is on schedule.

2. The Science Center shall develop a procedure for documenting project reviews. At a minimum the following information should be included in project review documentation:

- Date of review.
- Type of review (quarterly, 10/40/70, discipline).
- Names of reviewers and/or attendees.
- Response to recommended action items from the last review.
- Status, plans, and problems with data collection, data analysis, and report writing.
- Major findings.
- Cooperator/customer contacts.
- Training needs.
- Recommended follow-up or action items.
- Date for next review.

3. The Science Center shall develop a procedure for archiving project review comments, addressing the presence or absence of project deficiencies and all actions to fix deficiencies or document why a fix cannot be made.

DATA COLLECTION

Documentation of Technical Procedures

Written records of exactly how data are collected are critical to establishing the consistency, comparability, repeatability, and traceability of scientific data. The methods used to collect a specific data set shall be documented and the documentation shall be maintained with the data. For routine field activities, technical-procedure documents are a means of ensuring that detailed documentation is generated prior to data collection and shall be identified or prepared during the formal planning phase of the project, as applicable.

A **technical-procedure document** is a detailed description of a sequence of actions to be used to collect data to ensure repeatability of the work and comparability of results. If it is necessary to deviate from the technical-procedure documents when collecting data, then these deviations must be clearly described in the project records. When data-collection methods are new or experimental, a record of the conduct, progress, and results of these methods shall be maintained in a procedures notebook.

The following quality-assurance activities shall be performed by the Science Center.

1. Technical-procedure documents shall be prepared for routine field data collection that is performed in support of ground-water activities. The water-quality aspects of ground-water activities that are addressed in the quality-assurance plan for water quality need not be duplicated. Technical-procedure documents shall be in place prior to data collection and shall contain the following:

a. A cover sheet that indicates the technical-procedure document number, title, author or compiler, reviewer, approval, effective dates for the procedure, and identification number for any technical-procedure documents superseded by the current technical-procedure document.

b. Purpose of the technical procedure; for example, “this procedure explains how to measure water levels within 0.01 feet by using a chalked steel tape.”

c. Identification of materials and instruments used to collect data.

d. Quantitative statement of the accuracy of data collected using the procedure (for example, “to the nearest 0.1 foot”) and limitations on the use of these data.

e. Statements about the advantages, disadvantages, and assumptions of the procedure.

f. Step-by-step instructions to collect data that would enable an independent, qualified person to repeat the work and produce comparable results.

g. A description of how data collected by using the procedure are recorded and preserved.

h. A description of samples to be collected or used, if applicable.

i. A listing of technical references used to compile the technical-procedure document.

j. Attachments (field forms, operator's manual, diagrams, and other pertinent supporting information).

2. The technical procedure used to collect data shall be indicated on the field form.

3. The Science Center shall establish and maintain a file of technical-procedure documents.

a. Technical-procedure documents shall be identified with a unique number and cataloged and indexed.

b. The file shall be maintained by the Science Center ground-water specialist or designee.

c. The file shall contain all current and superseded versions of technical-procedure documents.

4. Deviations from approved technical procedures shall be documented by the project chief and reviewed by the Science Center ground-water specialist to determine if a formal revision of the technical-procedure document is warranted.

5. New or revised technical-procedure documents shall be reviewed by an independent reviewer and approved by the Science Center ground-water specialist.

a. Reviews shall address the following:

- Applicability and appropriateness of the selected methods for the intended purpose.
- Correctness of facts, figures, tables, and equations.
- Completeness and clarity of step-by-step instructions and technical content.
- Evaluation of the stated accuracy of the procedure.

b. Approval of technical-procedure documents used within the Science Center will be the responsibility of the Science Center ground-water specialist. Upon approval, the technical-procedure document shall be placed in the Science Center file and a copy of it forwarded to the Regional ground-water specialist.

Documentation of non-routine activities

1. When data-collection methods are new, non-routine, or research oriented and involve a high degree of professional judgment or trial-and-error, an active record of the conduct, progress, and results of the data collection shall be maintained in a procedures notebook. These records shall be prepared and maintained in accordance with the following:

a. Prior to use of a procedures notebook, the project chief shall consult with the Science Center ground-water specialist concerning the appropriateness of a non-routine method for planned data collection.

b. Each procedures notebook entry shall include the names of the individuals performing the work, the date on which the work was performed, and the name of the individual making the entries.

c. At the conclusion of the method development, procedures notebooks shall be placed in the project file.

2. The results of the technique developed in the procedures notebook shall be reviewed by the Science Center ground-water specialist to ensure that work is proceeding in a technically appropriate and relevant manner.

3. If the technique which has been documented in the procedures notebook becomes a routine procedure for the Science Center, then a technical-procedure document shall be developed.

Instrumentation

All instruments, devices, and equipment (including steel tapes) used to collect ground-water data are categorized as instruments. Because of the complexity of some instruments, their effect on the quality of the data may be unknown or unquantifiable.

To ensure the consistency, comparability, and repeatability of collected data, instruments must be identified, calibrated, maintained, and operated in an appropriate manner.

Calibration is the comparison of the output from an instrument to a standard or to the output from another instrument or procedure of known accuracy in order to detect, correlate, report, or eliminate by adjustment variations in the accuracy of the instrument being evaluated.

The following quality-assurance activities shall be performed by the Science Center.

1. Instruments used to collect data shall be identified with a unique identifier on the field form.

2. Calibration procedures and schedules shall be established for each instrument based on the stability characteristics of the instrument, required accuracy, intended use, manufacturer's recommendation, and other conditions that may affect the quality of the data. The calibration procedure and schedule shall be documented in the technical-procedure document that requires use of the instrument, or in a stand-alone technical-procedure document if not satisfactorily documented in the user’s manual for the instrument. Instruments shall be identified by type, manufacturer, and model. Calibration shall be performed whenever the accuracy of the instrument is suspect, regardless of the calibration schedule. Instruments consistently found to be out-of-calibration shall be repaired or replaced.

3. A log shall be maintained for each instrument requiring calibration. The log shall contain all information pertinent to calibration, whether performed by Science Center staff or by an outside organization or vendor. Calibration documentation recorded in the log shall include:

a. Name of organization and individual performing the calibration.

b. Identification of the instrument by type, manufacturer, model, serial number, or other unique and permanent identifier.

c. Identification of calibration standard, including the range and accuracy.

d. Identification of the document that describes the calibration process.

e. Date of current calibration and date or milestone for next scheduled calibration.

f. Records of instrument readings before and after any calibration.

4. Data collected with instruments found to be out-of-calibration shall be evaluated to determine the effect on the intended use of the data. Affected data shall be discarded or their limitations documented in the data base and in any application of the data.

5. All instruments used to collect data shall be operated in accordance with the manufacturer's manual, unless otherwise documented. Modifications to the manufacturer's operating procedure shall be appended to the manufacturer's manual, which shall be kept with the equipment at all times. Duplicate manuals for all instruments shall also be kept on file. Operating procedures may be included in technical-procedure documents.

6. Instrument maintenance shall be performed in accordance with the manufacturer's recommendations. A log shall be used to record maintenance performed.

Identification and Control of Samples

During the course of many ground-water investigations, samples of various types of earth materials are collected to supplement field observations or to allow laboratory tests, analyses, and measurements that are not possible to perform in the field. Types of samples include rock core, drill cuttings, soil, and outcrop. Because these samples can be critical scientific evidence to support interpretations, samples must be easily identifiable, handled and stored in a controlled manner, and be traceable. The relation between samples and the data set they represent must be maintained.

The following quality-assurance activities shall be performed by the Science Center.

1. Develop a unique identifier which shall be placed on each individual sample or sample container using materials and methods that are clearly visible, legible, and durable.

    a. The unique identifier, as well as other information that is critical for the intended use of a sample (such as orientation), shall be recorded on field forms and laboratory log books.

    b. If a sample is subdivided for analysis, the sample identifier shall be transferred to each part of the sample, or its container.

2. Establish a sample-control system to record information pertinent to each set of samples. This may be achieved by maintaining a log book, a set of forms, or other appropriate documentation. The sample-control system shall contain the following information for each sample:

    a. Unique identifier

    b. Type of sample and general description

    c. Source location specifications (x, y, z)

    d. Date and time of collection

    e. Reference to technical-procedure document or procedures notebook describing sample collection, handling, preservation, transportation, and storage.

    f. Storage location

3. Sample-control system documentation shall be placed in the project file.

DATA PROCESSING, REVIEW, AND STORAGE

A data-management plan describes the procedures used for data processing, review, and storage, and may also include archiving. After ground-water data are collected, they often are processed using one or more procedures, such as the application of time or datum corrections, and then are stored in computerized or physical files. Descriptive information on data-collection sites, such as well construction data and location, also should be stored. In general, data are most accessible and useful to the project chief and other Science Center employees, as well as to those outside the Science Center office, if they are stored in a computerized data base. Storage in a single data base also enables interpretations to be more easily verified and repeated. All water data collected as part of the routine data collection of the WRD, which are all ground-water data collected by basic data programs and Science Center projects (OGW Technical Memorandum 93.03) (see appendix), must be stored in computer files of the USGS National Water Information System (NWIS).

In addition, “all data collected by others -- such as cooperators, universities, or consultants --that are used to support published USGS documents and not published or archived elsewhere, shall be placed in NWIS” (Hubbard, 1992). Exceptions to these requirements are spatial data coverages and other data for which appropriate data-base capabilities do not exist in NWIS.

A quality data base is maintained by:

- checking data-base files against original data files to ensure accuracy,
- performing internal cross-checks of the data in the data base to identify anomalous data, and
- maintaining the original data in paper or electronic archives to ensure integrity.

Original data are those data -- from automated data-collection sites, laboratories, outside sources, and non-automated field observations -- unmodified as collected or received, once put into conventional units (engineering units, generally with a decimal) (Hubbard, 1992).

The following quality-assurance activities shall be performed by the Science Center.

1. All original data in paper form shall be placed in project or data-collection program files. Original data in electronic form shall be stored in NWIS. All original data shall be preserved unmodified as collected or received.

2. All data collected as part of the routine data collection of the WRD, and all existing data collected by WRD and others that are used to support published USGS documents and not published or archived elsewhere, shall be placed in NWIS unless excluded under current WRD

policy (Hubbard, 1992). Excluded data are spatial data coverages and other data that cannot be stored in NWIS

3. The Science Center shall prepare and implement a Science Center Data-Management Plan, which documents established policies, conventions, and responsibilities for data processing, data review, handling project and data-collection program files, and computerized data bases. OFR 94-61 (Martin and Cohen, 1994), offers an example of such a document. The Science Center Data-Management Plans shall:

- Describe the processing of each type of data through such steps as entry on a field form, data review, data entry, and filing of the original data. Data processing that is described in a technical-procedure document may be referenced.

- Include descriptions of filing systems for site data and maps, local well-numbering systems, requirements for field-checking sites, and Science Center-specific data-base management policies and practices.

- Indicate how the Science Center ensures that data are reviewed promptly after data collection. Data reviews shall verify that as data are collected, they are entered in the data base and that the data in the data base have been checked against the original data, including the processing of electronic data to original data, application of shifts and datums, correction of transducer drift, and so forth. Data reviews shall be documented during project reviews.

- Document any data bases external to NWIS. Documentation should include a description of data elements (data dictionary), information about the data base table or file structure, copies of customized program code, and information about any algorithms used by the data base to calculate results for storage or output. If the data base is described in a separate report, the documentation may be referenced by the Science Center Data-Management Plan and a copy of the documentation kept with the plan.

- Include a plan for performing periodic internal checks of ground-water data in NWIS and any other ground-water data bases to identify and correct anomalous data.

4. Data shall be reviewed promptly after any data-processing procedure is completed to ensure that the procedure was correctly applied and that the results are consistent both internally to the data set and with other data for the same site. This review shall be performed prior to publication or other dissemination to the general public and prior to the technical review of publications that contain the data or that use the data in interpretations. The Science Center shall establish a review schedule for data in addition to or in conjunction with other reviews. Reviews should be scheduled and implemented for data-collection programs as well as interpretive projects.

DATA ANALYSIS

Analysis of ground-water data includes activities ranging from simple statistical applications to the development and application of complex, numerical models. Quality assurance of data analysis begins with a well thought out and detailed workplan that describes methods and approaches of data analyses. Analysis procedures shall be reviewed as part of the proposal and workplan

development, and during project reviews as appropriate. The methods by which data, or the results of data analyses, are “interpreted,” such as the insight involved in the interpolation of water-level data to produce a potentiometric-surface map or the interpretation of the results of model simulations, cannot be completely documented. However such interpretations must be appropriately qualified, including descriptions of model limitations and data uncertainty.

Reviews of data-analysis procedures ensure that selected analysis techniques are appropriate for meeting project objectives. Data-analysis techniques are identified, at least preliminarily, during development of the project workplan. During project reviews, at about 10 percent of project completion, after a better understanding of the project is developed, data-analysis procedures should be reviewed for suitability in meeting the project’s objectives. At about 40 percent of project completion, data-analysis techniques should be reviewed to ensure that preliminary analyses produce valid results. If modifications to procedures are warranted, these modifications are documented in review comments. At a point when data analysis is complete, at approximately 70 percent of project completion, all data that were collected for a project, and the results of intermediate and final data analyses, are assembled and reviewed. Original data, data analyses, and data that were collected but not used in analysis, along with reasons for the exclusion, are documented as a part of the project review and placed in the project file.

The following quality assurance activities shall be performed by the Science Center.

1. Data-analysis procedures shall be referenced and new data-analysis procedures, including those implemented by software, shall be documented in a report released prior to, or as part of, the report giving the results of that technique. Documentation might include:

- a description of the theoretical basis and computational procedure in sufficient detail to perform the analysis,
- all data requirements or options for the data-analysis procedure, and
- comparisons of the technique with known or accepted solutions.

Office of Ground Water Technical Memorandums 79.04, 91.04, and 96.04 (see appendix) have outlined documentation requirements for data-analysis procedures implemented by software.

2. The results of data analysis shall not be presented at a finer spatial or temporal resolution than supported by the input data. The results shall not be displayed with an accuracy that exceeds the capability of the analysis or the accuracy of the data-collection methods. Interpretations of data analysis, shall be appropriately qualified, including descriptions of limitations and data uncertainty.

3. Science Centers shall establish a written policy for reviewing data-analysis procedures and documenting the review. The results of any data analysis shall be reviewed, prior to release, to ensure that the analysis is valid. The reviewer shall be provided with any necessary background information to adequately perform the review. The Science Center shall establish a procedure for resolving the reviewers’ concerns that ensures that the review comments are carefully considered and revisions made, if appropriate, and that direct interaction occurs between the project chief and the reviewer. The Science Center also shall establish and implement an archiving process for the review documents.

PUBLICATIONS

Disseminating information to Congress and the general public has been required of the USGS, since its creation in the Organic Act of 1875. The report review process ensures the quality of the written report, which is the culmination and final result of the training, planning, data collection, and data analysis. To satisfy national responsibilities and to produce accurate and timely reports, the Science Center shall perform the following quality-assurance activities.

1. All ground-water data collected in USGS data-collection programs and interpretive and research projects shall be published in a timely manner. Data in NWIS that have been reviewed and approved are available to the general public, and can be considered published.

2. The Science Center Director in consultation with the Office of Ground Water shall approve, in writing, any exceptions to the requirement to publish all data, including data collected under an agreement of confidentiality.

3. Data furnished by sources other than WRD may be used for analysis and published if the source of the information approves and if (1) the data have been appropriately quality assured, or (2) the data have not been thoroughly quality-assured but are described in terms of appropriate qualifications and limitations. In either case, the source of the data must be acknowledged. Care should be taken to assure that data are published with the correct number of significant figures.

4. Reports shall be reviewed and approved according to current Science Center and WRD policy.

ARCHIVING

Archiving is the final step in the processes of data collection, analysis, and interpretation.

Although the report represents the summary of the current work, the data and its interpretation should be available for further analysis.

Archiving is the systematic process of storing data and information to protect it from change or loss, by providing the necessary security.

Electronic archiving is the systematic process of removing data from active, on-line computer storage and preserving it with the capability to recover the data.

To quality assure the archiving process, the following steps shall be performed by the Science Center:

1. All data shall be archived as specified by current WRD policy.

2. All model related computer files and appropriate simulation results shall be archived as outlined in OGW Technical Memorandum 93.01 (see appendix).

3. All aquifer-test data and results shall be archived as outlined in OGW Technical Memorandum 94.02 (see appendix).

4. An Archiving Plan for the Science Center which documents the disposition of all project information upon completion of Science Center projects shall be established. The Archiving Plan shall document the archiving process and the responsibilities of personnel assigned to archiving tasks. The disposition of technical-procedure documents and procedures notebooks developed for an individual project should be described in the Archiving Plan.

Internal California District policy (Instruction 1641.1A, July 9, 1991, Ron Fogelman, California District, written communication) and Indiana District data management and archival policies (Martin and Cohen, 1994) are examples of archiving plans. Parts of the project files may be incorporated into the Districtwide file system, as appropriate.

AUDIT

Audits are designed to ensure that all tasks described in the GWQAP are being performed. Audits will be performed during the Technical Science Center Reviews.

Audits are documented quality-assurance activities performed to determine compliance with the GWQAP and associated documents and the effectiveness of their implementation. Audits include observing field data-collection activities and reviewing office documentation. Audits are usually peer reviews.

The following quality-assurance activities shall be performed by the Office of Ground Water.

1. Develop an Audit Plan to monitor compliance with the requirements of the GWQAP. Audits apply to all ground-water field and office activities. The Audit Plan identifies the activities to be audited, scope of the audit, requirements governing the audit, organizations to be notified (if any), applicable documents, and tentative audit schedule. The audit shall, as a minimum, address the following questions:

- Do training plans, workplans, technical-procedure documents, calibration records, and maintenance logs exist, are they complete, and are the plans and technical-procedure documents being implemented?

- Do data-management and archiving plans exist, are they complete and up-to-date, and are they being implemented?

- Are project reviews being performed and documented according to the GWQAP?

2. Conduct the audit during the technical review of the Science Center program.

3. Document all comments and recommendations in the technical review report.

4. Send all comments and recommendations to the Regional Hydrologist and the Science Center.

The Region is responsible to see that all recommendations are addressed. The Office of Ground Water will receive copies of all correspondence between the Science Center and the Regional Hydrologist relating to audits and audit plans.

SUMMARY

This report provides a plan to direct the quality assurance of ground-water activities in Science Center offices of the USGS, and presents policies pertaining to training; planning; data collection, processing, review, analysis, and storage; publications; archiving; and audits as they relate to these activities. The implementation of a GWQAP will enhance the consistency, accountability, comparability, traceability, and repeatability of ground-water activities of the USGS.

REFERENCES CITED

Green, J.H., 1991, WRD Project and Report Management Guide: U.S. Geological Survey Open-File Report 91-224, 152 p.

Hubbard, E.F., compiler, 1992, Policy recommendations for management and retention of hydrologic data of the U.S. Geological Survey: U.S. Geological Survey Open-File Report 92-56, 32 p.

Martin, J.D., and Cohen, D.A., 1994, Policy and procedures for the management and archival storage of data collected for hydrologic investigations of the U.S. Geological Survey, Indiana District: U.S. Geological Survey Open-File Report 94-61, 36 p.

Schroder, L.J., and Shampine, W.J., 1992, Guidelines for preparing a quality assurance plan for district offices of the U.S. Geological Survey: U.S. Geological Survey Open-File Report 92-136, 14 p.

Shampine, W.J., Pope, L.M., and Koterba, M.T., 1992, Integrating quality assurance in project work plans of the U.S. Geological Survey: U.S. Geological Survey Open-File Report 92-162, 12 p.

APPENDIX B

PARTIAL LIST OF REFERENCES FOR GROUND-WATER DATA-COLLECTION ACTIVITIES

U.S. Geological Survey Publications:

Techniques of Water Resources Investigations:

Bennett, G.D., 1976, Introduction to ground-water hydraulics, a programmed text for self-instruction: USGS--TWRI Book 3, Chap. B2.

Cooley, R.L., and Naff, R.L., 1990, Regression modeling of ground-water flow: USGS—TWRI Book 3, Chap. B4.

Franke, O.L., Reilly, T.E., and Bennett, G.D., 1987, Definition of boundary conditions in the analysis of saturated ground-water flow systems: An introduction: USGS—TWRI Book 3, Chap. B5.

Haeni, F.P., 1988, Application of seismic refraction techniques to hydrologic studies: USGS--TWRI Book 2, Chap. D2.

Higgs, H.C., 1968, Some statistical tools in hydrology: USGS--TWRI Book 4, Chap. A1.

Jenkins, C.T., 1970, Computation of rate and volume of stream depletion by wells: USGS--TWRI Book 4, Chap. D1.

Keys, W.S., and McCary, L.M., 1971, Application of borehole geophysics to water-resources investigations: USGS--TWRI Book 2, Chap. E1.

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: USGS—TWRI Book 2, Chap. E2.

Konikow, L.F., and Bredenhoeft, J.D., 1978, Computer model of two-dimensional solute transport and dispersion in ground water: USGS--TWRI Book 7, Chap. C2.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: USGS--TWRI Book 6, Chap. A1.

Reed, J.E., 1980, Type curves for selected problems of flow to wells in confined aquifers: USGS--TWRI Book 3, Chap. B3.

Reilly, T.E., Franke, O.L., and Bennett, G.D., 1987, The principle of superposition and its application in ground-water hydraulics: USGS--TWRI Book 3, Chap. B6.

Stallman, R.W., 1971, Aquifer-test design, observation, and data analysis: USGS—TWRI Book 3, Chap. B1.

Trescott, P.C., Pinder, G.F., and Larson, S.P., 1976, Finite difference model for aquifer simulation in two dimensions with results of numerical experiments: USGS--TWRI Book 7, Chap. C1.

Zody, A.A.R., Eaton, G.P., and Mabey, D.R., 1974, Application of surface geophysics to ground-water investigations: USGS--TWRI Book 2, Chap. D1.

Office of Ground Water Technical Memorandums (cannot be referenced or distributed):

69.08	11/21/68	Applications of the digital computer for aquifer evaluation
70.04	08/14/69	Determining the ratio of horizontal to vertical permeability by aquifer-test analysis
76.05	11/07/75	Computer program for ground-water systems, "Documentation of finite-difference model for simulation of three-dimensional ground-water flow."
77.01	11/19/76	Supplement to the computer program documentation for modeling three-dimensional ground-water systems, (distributed as Memorandum No. 76.05)
77.06	05/09/77	Corrections to computer code for modeling three-dimensional ground-water flow
78.04	02/10/78	A new field technique for determining air permeability hydraulic conductivity in the unsaturated zone,
81.01	10/07/80	A computer program for interpolation of geohydrologic data using the method of "Kriging."

Water Resources Division—Ground-Water Notes (cannot be referenced or distributed):

1	Cyclic fluctuations of water level as a basis for determining aquifer transmissibility, by J.G. Ferris
2	Composite type curve for analyzing ground-water pumping-test data, by W.C. Walton and W.J. Dresher.
3	Nonequilibrium type curves modified for two-well systems, by R.W. Stallman
4	Graphic method for plotting field pumping-test data, by G.A. LaRocque
7	A generalized graphical method of evaluating formation constants and summarizing well-field history, by H.H. Cooper, Jr., and C.E. Jacob
8	One the flow of water in an elastic artesian aquifer, with notes on elasticity of the Lloyd Sand on Long Island, New York, by C.E. Jacob
13	Radial flow in a leaky artesian aquifer, by C.E. Jacob
14	The effect of a well on the flow of a nearby stream, by C.V. Theis
17	Equation for lines of flow in vicinity of discharging artesian well, by C.V. Theis

18 Computation of drawdowns at equilibrium caused by wells drawing water from an aquifer fed by a finite straight line source, by C.V. Theis

21 The significance and nature of the cone of depression in ground-water bodies, by C.V. Theis

22 Drawdown in wells responding to cyclic pumping, by c.V. Theis and R.H. Brown

23 Estimating transmissibility from specific capacity, by C.V. Theis and others

24 Stream-bed percolation in development of water supplies, by M.I. Rorabaugh

25 The slug test for estimating transmissibility, by J.G. Ferris and D.B. Knowles

26 Drawdown patterns for two-well systems as applied to straight-line- boundary conditions, by S.M. Lang

32 Problems of ground disposal of nuclear wastes, by C.V. Theis

33 Method of determining the coefficient of storage from straight-line plots without extrapolation, by S.W. Lohman

34 The source of water derived from wells essential factors controlling the response of an aquifer to development, by C.V. Theis

35 An equation for potential distribution about a well being bailed, by H.E. Skibitzke

36 Ground-water movement in a rectangular aquifer bounded by four canals, R.H. Brown

37 The development of the cone of depression around a pumped well in an infinite strip aquifer subject to uniform recharge, by R.H. Brown

38 Notes on the use of temperature data for computing ground-water velocity, by R.W. Stallman

39 The disposal of low and intermediate level radioactive wastes to the ground, by C.V. Theis

Other Publications:

Bennett, G.D., and Patten, E.P., Jr., 1960, Borehole geophysical methods for analyzing specific capacity of multiaquifer wells: USGS Water-Supply Paper 1536A.

_____1962, Constant-head pumping test of a multiaquifer well to determine characteristics of individual aquifers: USGS Water-Supply Paper 1536G.

Bentall, R., 1963, Methods of determining permeability, transmissibility, and drawdown: USGS Water-Supply Paper 1536I.

_____1963, Shortcuts and special problems in aquifer tests: USGS Water-Supply Paper 1545C.

Cooper, H.H., Jr., and Rorabaugh, M.I., 1963, Ground-water movements and bank storage due to flow stages in surface streams: USGS Water-Supply Paper 1536J.

Cooper, H.H., Jr., Bredehoeft, J.D., and Papadopulos, I.S., 1967, Response of a finite- diameter well to an instantaneous charge of water: Water Resources Research, v. 3, no. 1.

Cooper, H.H., Jr., and others, 1964, Sea water in coastal aquifers: USGS Water-Supply Paper 1613C.

Durbin, T.J., 1978, Calibration of a mathematical model of the Antelope Valley ground- water basin, California: USGS Water-Supply Paper 2046.

Ferris, J.G., and others, 1962, Theory of aquifer tests: USGS Water-Supply Paper 1536E.

Grove, D.B., 1976, A model for calculating effects of liquid waste disposal in deep saline aquifer: USGS Water-Resources Investigations Report 76-61.

_____1979, Revision of the documentation for a model for calculating effects of liquid waste disposal in deep saline aquifers: USGS Water-Resources Investigations Report 79-96.

Hubbert, M.K., 1940, The theory of ground-water motion: Journal of Geology, v. 48, no. 8, pt. 1.

Jorgensen, D.G., 1980, Relationships between basic soils-engineering equations and basic ground-water flow equations: USGS Water-Supply Paper 2064.

Konikow, L.F., 1977, Modeling chloride movement in the alluvial aquifer at the Rocky Mountain Arsenal, Colorado: USGS Water-Supply Paper 2044.

Larson, S.P., 1978, Direct solution algorithm for the two-dimensional ground-water flow model: USGS Open-File Report 79-202.

Lohman, S.W., 1972, Ground-water hydraulics: USGS Professional Paper 708.

McCary, L.M., 1980, Use of geophysical logs to estimate water-quality trends in carbonate aquifers: USGS Water-Resources Investigations Report 80.57.

Meyer, W.R., 1962, Use of a neutron-moisture probe to determine the storage coefficient of an unconfined aquifer: in Short Papers in Geology, Hydrology, and Topography: USGS Professional Paper 450-E.

Ofgren, B.E., 1968, Analysis of stresses causing land subsidence: in Geological Survey Research: USGS Professional Paper 600-B.

Papadopulos, I.S., 1963, Preparation of type curves for calculating T/S of a wedge- shaped aquifer: in Short Papers in Geology and Hydrology: USGS Professional Paper 475-B.

Pinder, G.F., Bredenhoeft, J.D., and Cooper, H.H., Jr., 1969, Determination of aquifer diffusivity from aquifer response to fluctuations in river stage: Water Resources Research, v. 5, no. 4.

Poland, J.F., and others, 1975, Land subsidence in the San Joaquin Valley, California: USGS Professional Paper 437-H.

Prill, R.C., and Aronson, D.A., 1978, Ponding-test procedure for assessing the infiltration capacity of storm-water basins, Nassau County, New York: USGS Water-Supply Paper 2049.

Remson, I., McNeary, S.S., and Randolph, J.R., 1961, Water levels near a well discharging from an unconfined aquifer: USGS Water-Supply Paper 1536B.

Schneider, R., 1962, An application of thermometry to the study of ground water: USGS Water-Supply Paper 1544B.

Skibitzke, H.E., and da Costa, J.A., 1962, The ground-water flow systems in the Snake River Plain, Idaho—An idealized analysis: USGS Water-Supply Paper 1536D.

Stallman, R.W., 1963, Electric analog of three-dimensional flow to wells and its application to unconfined aquifers: USGS Water-Supply Paper 1536H.

_____1964, Multiphase fluids in porous media—A review of theories pertinent to hydrologic studies: USGS Professional Paper 411-E.

Stallman, R.W., and Papadopulos, I.S., 1966, Measurement of hydraulic diffusivity of wedge-shaped aquifer: USGS Professional Paper 514.

Sorey, M.L., 1978, Numerical modeling of liquid geothermal systems: USGS Professional Paper 1044-D.

Trescott, P.C., 1976, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: USGS Open-File Report 75-438.

Trescott, P.C., and Larson, S.P., 1976, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: USGS Open-File Report 76-591.

Weeks, E.P., and Sorey, M.L., 1973, Use of finite-difference arrays of observation wells to estimate evapo-transpiration from ground water in the Arkansas River Valley, Colorado: USGS Water-Supply Paper 2029C.