SENEGAL RIVER VALLEY GROUND-WATER MONITORING PROJECT: SUMMARY REPORT ON PIEZOMETER EVALUATION, FEBRUARY-MARCH 1989

By Edward L. Bolke and Jerry C. Stephens

U.S. GEOLOGICAL SURVEY
Open-File Report 89-411

Prepared for the
ORGANISATION POUR LA MISE EN VALEUR DU FLEUVE SENEGAL
and the U.S. AGENCY FOR INTERNATIONAL DEVELOPMENT

Portland, Oregon
1989

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary
U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

For addition information write to:	Copies of this report can be purchased from:
U.S. Geological Survey 10615 S.E. Cherry Blossom Drive Portland, Oregon 97216	U.S. Geological Survey Books and Open-File Reports Section Building 810, Federal Center Box 25425 Denver, Colorado 80225

CONTENTS

ILLUSTRATIONS

SENEGAL RIVER VALLEY GROUND-WATER MONITORING PROJECT: SUMMARY REPORT ON PIEZOMETER EVALUATION, FEBRUARY-MARCH 1989

--

By Edward L. Bolke and Jerry C. Stephens

--

ABSTRACT

In response to a request from U.S. Agency for International Development, the U.S. Geological Survey provided technical assistance to the Senegal River Valley Ground-water Monitoring Project in western Africa. The technical assistance consisted of evaluating approximately 600 piezometer wells, constructed near the Senegal River, to determine if the piezometers were installed in such a manner that accurate hydraulic data could be obtained from the wells. The hydraulic data will be used to determine the head difference between the shallow and deep aquifers in the Senegal River valley, as well as between the aquifers and the Senegal River.

Field examinations of 27 randomly selected piezometer installations revealed that construction and stability of well footings was satisfactory and that well depths and water levels were within 10 percent or less of reported values. Evaluation of water-level hydrographs for 36 randomly selected piezometer wells indicated that ground-water levels fluctuated seasonally in all wells, with highs in October-November and lows in May-June, corresponding, respectively, to peak- and low-flow stages of the Senegal River. Maximum annual fluctuations in ground-water levels ranged from a few tenths of a meter to about 3 meters. Hydraulic conductivities calculated from slug-injection test data collected by project personnel for 137 piezometers in the lower Senegal River delta ranged from 1.0×10^{-3} at wells in medium- to fine-grained sand to 8.0×10^{-7} centimeters per second at wells in silty clay.

The results of these evaluations indicate that the piezometers are properly installed and providing valid data.

INTRODUCTION

Several reports (for example, Illy, 1973; Audibert and Filippi, 1984) have been written on the hydrogeology of the Senegal River basin. These reports, useful as they are, lack sufficient data from which detailed hydrologic analyses can be made, although the reports provide adequate general background information on the hydrogeology of the area. Illy (1973, figs. III and IV) describes some anomalies as related to hydraulic gradient northeast and south-southwest of Podor, and indicates that the Senegal River is losing water all along its reach in this area. These water-table maps show two areas of large "sinks" or drains; the hydraulic head decreases to about 15 meters below sea level east of Podor and to about 25 meters below sea level northeast of Podor (Illy, 1973, fig. III, p. 51). Several questions arise: Are the data valid? Where does the water discharge? Are the land-surface elevations of the wells accurate? What, if any, hydraulic connection exists between the river and the materials in which these water levels were measured? The answers to these and other questions related to development of the water resources of the Senegal River valley are expected to come, in large part, from data to be obtained from the Senegal River Valley Ground-water Monitoring Project, which is in part supported by the U.S. Agency for International Development (USAID).

In response to a request from USAID, the U.S. Geological Survey assigned Edward L. Bolke for 2 weeks in February-March 1989 to provide technical assistance to the Senegal River Valley Ground-water Monitoring Project in Senegal, Mauritania, and Mali, western Africa. The principal objectives of this major, multinational project, as identified in the "Project Paper" (the basic project plan), address:

(1) Ground-water dynamics, including water logging and salinization, in and around existing irrigated areas;

(2) Recharge-discharge relations of the Senegal River, its valley aquifers, and contiguous regional aquifers;

(3) Changes in the ground-water regime caused by the construction of the Diama and other dams and the resulting alterations of river-flow regime;

(4) Water quality in domestic and livestock wells resulting from changes in river flow, irrigation, and application of fertilizers, pesticides, and other materials; and

(5) Potential for irrigation development from ground water in selected areas.

This paper describes the results of the evaluation of a field-piezometer monitoring system with respect to data quality conducted during February-March 1989. Additional aspects of the project to be evaluated included: the existing computer system as a basic tool for further hydrologic studies, existing hydrologic models with respect to their application to the ground-water system in the project area; and the potential need for and scope of activities of additional short-term technical assistance specialists.

The principal purpose of the trip to the Senegal River basin of Senegal, Mali, and Mauritania (see fig. 1) was to determine if approximately 600 piezometer wells were installed in such a manner that accurate hydraulic data could be obtained from the wells. The hydraulic data will be used to determine the head difference between the shallow and deep aquifers in the alluvium in the Senegal River valley, as well as between the aquifers and the Senegal River. This distribution of head, laterally and vertically, will subsequently allow determination of direction of ground-water flow. Ground-water data collected before completion of the Diama Dam can be used to analyze ground-water flow direction prior to dam completion; likewise, data collected after dam completion can be used to determine the effect of dam construction on the flow system.

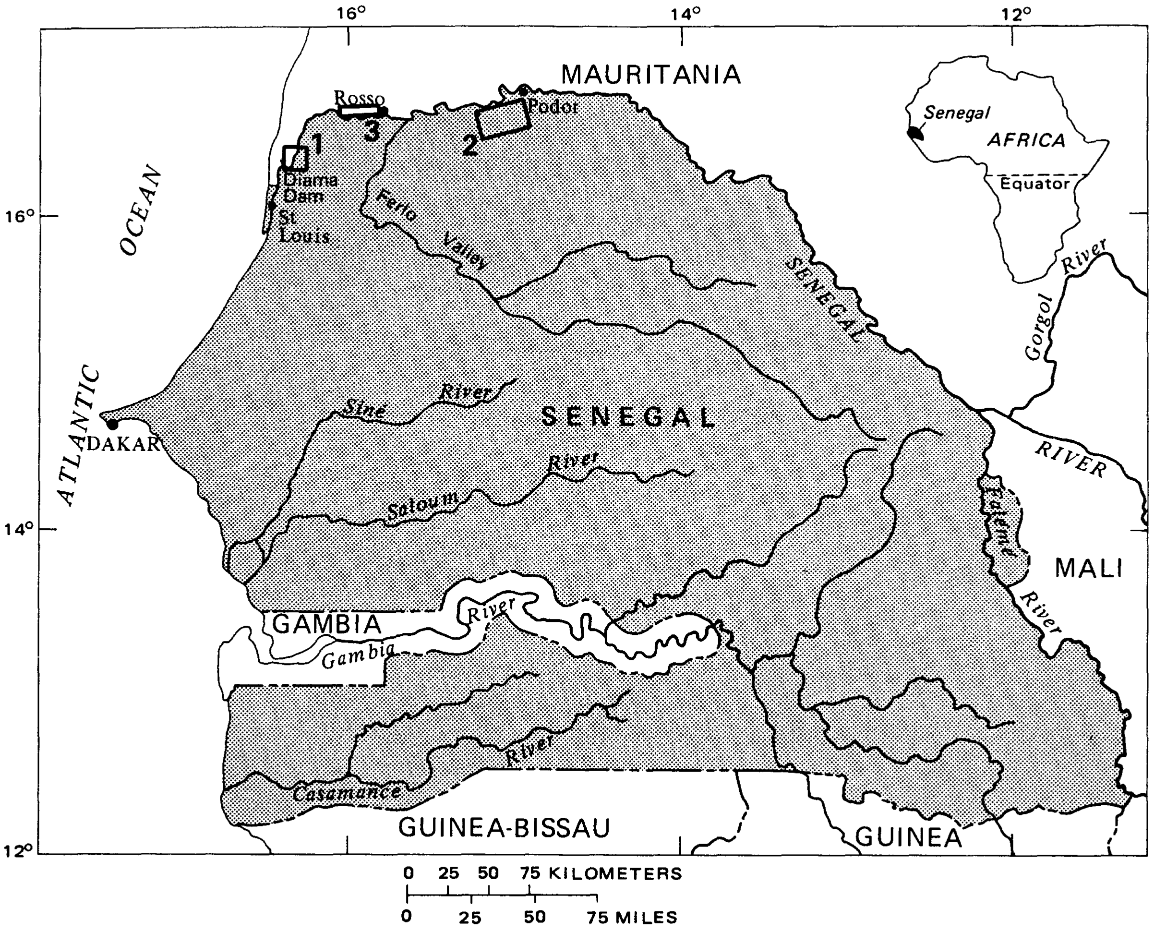

Figure 1. – Location of Senegal area (Numbers refer to areas cited in text where field evaluations were conducted).

EVALUATION OF PIEZOMETER DATA

Because of the large quantity of information available and time constraints, tasks identified to evaluate the piezometer network were as follows.

- o Review overall project goals as related to piezometer placement and installation. This includes review of the Project Paper, associated documents, and findings by earlier consultants.

- o Review the data collected from piezometer wells to date. These data include plots of well locations, lithologic logs, screened intervals, and water levels of randomly selected wells. The wells having plotted water-level hydrographs were randomly selected from both banks of the river, principally along established section lines. The hydrographs are used to determine the relation, if any, among water-level fluctuations, changes in river stage, irrigation practices, dam construction, changes in precipitation patterns, and tidal effects. Wells in which water levels do not fluctuate probably are inoperative and may need cleaning, conditioning, or replacement.

- o Visit randomly selected wells for comparison of constructed depth and actual depth, as well as observation of techniques used for water-level measurements.

- o Review results of hydraulic conductivity computations from slug-injection tests performed on most of the piezometers. The rationale here is that similar material should have similar hydraulic conductivity.

RESULTS OF PIEZOMETER EVALUATION

Three areas of the project were visited on March 3, 5, and 9, 1989, to inspect piezometer installations and to verify the depth of the piezometers. These areas, which are shown in figure 1 were,

(1) near Diama Dam in both Senegal and Mauritania,

(2) the left bank of the Senegal River south and west of Podor, and

(3) the vicinity of Rosso in Mauritania.

Twenty-seven sites were visited; water levels and piezometer depths were verified at about 80 percent of the sites. The measured depths were within 4 percent of the prescribed construction depth at three-fourths of the sites and within 10 percent of the stated construction depths for the remainder. The tube of one well apparently is bent or plugged because a sounding probe could not be advanced easily down the tube.

The construction and stability of each piezometer footing was inspected and found to be satisfactory. The concrete spalled at only one of the sites visited; the concrete was repaired. In another case, the hinges on a cover plate had been vandalized. The cover was still in place and the piezometer tube intact.

Water-level hydrographs from 36 randomly-selected piezometer wells were plotted for the period of record (July 1987 to February 1989). The hydrographs were examined for evidence of hydraulic connection with the aquifer or hydrogeologic unit in which they were constructed. Fluctuations in the water levels indicate hydraulic-pressure changes that occur in the aquifer.

Water levels fluctuate in all the piezometers for which hydrographs were examined. Annual fluctuations vary from about 3 meters in piezometers near the confluence of the Senegal and Gorgol Rivers to a few tenths of a meter in piezometers near Podor to about a meter in piezometers near Diama Dam. Seasonal water-level highs occur in all 36 hydrographs during October-November, corresponding to peak stages of the Senegal River. Similarly, the lows in the hydrographs occur during May-June during lowest stages of the river. A few minor anomalies that exist in the data can be reviewed and corrected by the project team.

Computations of hydraulic conductivity, as determined from slug-injection tests, were analyzed using data from 137 piezometers located in the lower Senegal River delta. The tests were conducted by using the method of Ferris and Knowles (1963). The hydraulic conductivities calculated by using this method ranged from 1.0×10^{-3} centimeters per second at piezometers completed in medium- to fine-grained sand to 8.0×10^{-7} centimeters per second at those completed in silty clay or a combination of sand, silt, and clay. Nearly 80 percent of the piezometers are finished in the fine- to medium-grained sand. Values of hydraulic conductivity given in published technical journals and papers (see Morris and Johnson, 1966 and Ghislain de Marsily, 1986) for these lithologies range from about 1.0×10^{-3} centimeters per second for fine sand to about 1.0×10^{-7} centimeters per second for silt and (or) silty clay. Thus, the results obtained from the project piezometers are reasonable and consistent with accepted values.

Because water levels in the piezometers respond to changes in hydraulic stress, it can be concluded that they are functional. Most of the piezometers visited were within about 4 percent of their designed depth. A few are within 10 percent of the designed depth, but these placement differences are not significant because of the heterogeneous nature of the alluvial material and the difficulty of obtaining representative samples and subsequent definition of the lithology. In summary, the random selection of piezometers for analysis and the favorable results obtained therefrom attests to the reliability of the piezometer installations and operation of the network.

OTHER WORK NEEDED

The objectives of the Senegal River valley project require a system analysis of the entire Senegal River valley. The ultimate objective of the project is to present a method to the Organisation pour la Mise en Valeur du Fleuve Senegal (OMVS) for managing the resource. The large amount of reliable ground-water data available in the valley is suitable for simulation of the flow system by using a digital computer model. The model, once it is properly constructed and calibrated, could be a useful tool for fulfilling this objective. Manual methods of analysis of the data would be tedious, time consuming, and might not be adequate for describing the total flow system. The generalized report outlines that follow indicate the work that is needed in each of the three planned project phases.

PHASE I -- BASIC DATA COLLECTION AND COMPILATION

Work currently (1989) is being completed.

PHASE II -- INTERPRETIVE REPORT ON HYDROLOGY OF SENEGAL RIVER BASIN

- Introduction
  - Location
  - Purpose
  - Geography
  - Population
  - Economy
  - Climate (precipitation, temperature, evaporation)
  - Geologic setting
  - General description, age, and structure of rocks
- Hydrology
  - Surface water
    - Location of dams, completion dates, and stage
    - Location of stream gages and period of record
    - River-bottom profile
    - River-stage profile
    - Surface-water statistics

Daily, monthly, and annual mean flows
Flood-frequency analysis
Low-flow duration curves
Surface-water diversions
Ground water
Hydrologic boundaries
Aquifer description
Thickness, structure, and areal extent maps (each aquifer)
Thickness, structure, and areal extent of confining beds (maps)
Hydraulic characteristics (horizontal conductivity) and estimates of vertical hydraulic conductivity and storage coefficients for each aquifer and confining bed
Ground-water recharge
Precipitation, streams, irrigation
Ground-water movement
Hydraulic head maps of each aquifer
General direction of flow within each aquifer, between aquifers, and between aquifers and streams
Ground-water discharge
Streams, wells, and evapotranspiration from water table
Water quality
Delineation of salt-water zone from salt-water wedge in river and zone of diffusion along salt-water interface
Map of specific conductance, relation to dissolved solids and other ions from farm practices
Additional data and analyses needed to allow appropriate management of the water resources and determine the feasibility of applying a ground-water flow model

PHASE III - GROUND-WATER FLOW MODEL -- if feasible
Description of model
Model input data arrays (discretized from Phase II)
Grid dimensions (number and size of cells)
Boundary conditions each cell, each layer
Hydraulic head each layer
Bottom of upper layer
Tops and bottoms of lower layers
Lateral hydraulic conductivity each layer
Vertical hydraulic conductivity between layers
Recharge from precipitation (top active layer)
Recharge from irrigation (top active layer)
River data each river cell
Bottom, stage, hydraulic conductivity
Evapotranspiration from water table (top active layer)
Storage coefficient estimate (if model is time-average steady state)
Calibration and verification of model (Generally consists of systematic adjustment of least known variable until heads calculated by the model approximate the heads measured. The least known variable probably is the hydraulic conductivity of each layer).
Model output
Distribution of hydraulic head each layer
Water budget
Leakage to or from the streams for each layer for each cell

Phase III, if determined in Phase II to be feasible, applies to a steady-state or time-averaged model (period of time selected is discretionary but would be based on the data, and could be monthly, annually, or for several years). Heads and rates of flow would be calculated as averages over the selected period. The main purpose of this model would be to simulate the flow system to help understand the relation between ground and surface water.

If a transient analysis, in which heads and flows change with time, is needed for predictive capability, then additional data synthesis is required as follows:

A calibrated estimate of the storage properties for each layer;

Data arrays for each selected time period for each parameter causing ground-water levels to fluctuate, specifically:

- Recharge from precipitation;
- Recharge from irrigation;
- Streamflow diversions;
- Surface-water regulation by dams;
- Evapotranspiration; and
- Water levels throughout period of analysis.

It is noted that pumping from the ground-water system is minimal and can be neglected. It also is noted that saltwater is present in ground water at shallow depths as indicated from samples taken from piezometers in the lower part of the river valley. If ground-water pumpage were to be increased substantially, then a different model having a sharp or diffuse interface at the freshwater-saltwater contact would need to be constructed. Note is made of the possibility that heads in deeper aquifers may be residual heads from the low sea levels that existed during Pleistocene time and that the position of the saltwater interface may not be in equilibrium with the flow system in the shallow alluvial aquifers.

MISCELLANEOUS OBSERVATIONS

Slug-injection tests and aquifer tests are not necessarily the most accurate methods of calculating hydraulic conductivity of an aquifer. These analytical methods require numerous assumptions about the flow system including geometry, isotropy and heterogeneity of the aquifer boundaries, well construction, and degree of penetration into the aquifer by wells. The results commonly are inaccurate. Simulation by use of a ground-water-flow model, if done properly, can provide a way to determine areal values of hydraulic conductivity because the model can integrate the effects of (1) boundaries, such as no flow or river connection; (2) areal changes in vertical and lateral hydraulic conductivity; and (3) change in aquifer geometry.

The largest stresses on the ground-water system apparently are evapotranspiration and recharge from the Senegal River during the wet season (August-November). Available data indicate evaporation rates range from 8 millimeters per day during the wet season to 14 millimeters per day during the dry season. This translates to about 4 meters per year before applying a pan-evaporation coefficient, which reduces the evaporation rate value by 30 or 40 percent. It was noted that ground-water levels rose by about 3 meters near the mouth of the Gorgol River during the wet season.

TRAINING FOR MODEL CONSTRUCTION

A course on ground-water modeling is needed to provide project participants with an intensive learning experience along with a comprehensive knowledge of personal computer software application in ground-water problems. It would be highly desirable for project hydrologists Denis Richard and Ousmane Ngom to attend such a course. With their combined expertise and first hand knowledge of the Senegal River valley, they could expedite the construction of a model for the valley. Likewise, it would be beneficial if they could spend some additional time working with a project modeling team, perhaps in a District office of the U.S. Geological Survey.

Another option would be to have a hydrogeologist from U.S. Geological Survey construct the model. The advantage is that the mechanics of the model would not have to be learned. The main disadvantage is that the U.S. Geological Survey modeler would have to learn the flow system before proceeding with model construction. Additionally, many of the documents are written in French and would require translation into English, which may pose a problem for completing the work in a timely manner. If this latter option is considered feasible, the U.S. Geological Survey hydrogeologist might do the modeling from his or her home office. Communication difficulties could obviate this option, but TELEX[1] could be used extensively along with occasional visits to the project area by the hydrogeologist. This option may be the least desirable of the two.

MANPOWER AND TIMELINES

The time and manpower needed to complete Phase I was not evaluated. The time and manpower needs for Phase II and III are estimated as follows:

> The time estimated to complete Phase II is approximately 6 months <u>after</u> Phase I is completed. It is estimated that Phase II will require an estimated 6 months each of Denis Richard's and Ousmane Ngom's time.
>
> The time estimated to complete Phase III, which is entirely dependent on completion of Phase II, would be an additional 6 months. It is likewise necessary that 6 months each of Richard's and Ngom's time be expended on this phase of the project.

---

[1] Use of brand names in this report is for identification purposes only and does not constitute an endorsement by the U.S. Geological Survey

SUMMARY

In response to a request from the U.S. Agency for International Development, the U.S. Geological Survey assigned Edward L. Bolke for 2 weeks in February-March 1989 to provide technical assistance to the Senegal River Valley Ground-water Monitoring Project in Senegal, Mauritania, and Mali, western Africa. The principal objectives of this project address: ground-water dynamics in and around existing irrigated areas, recharge-discharge relations of the Senegal River and contiguous regional aquifers, changes in the ground- and surface-water regimes caused by the construction of dams, water quality, and the potential for irrigation development from ground water.

Overall, the project appears to be progressing satisfactorily. Phase I work is producing accurate and reliable data from the Senegal River basin. This phase will be completed in the next several months. Most projects of this type involving ground-water/surface-water relations have substantially less data than have been collected for this project.

The principal tasks identified for the 2-week technical assistance mission were to evaluate the field-piezometer monitoring system installed in the project area, the project's existing computer system as a basic tool to support further hydrologic studies, and existing hydrologic models with respect to their applicability to the project ground-water system.

The existing monitoring system consisting of 600 piezometer wells was evaluated based on field examination of 27 piezometer installations and review of water-level hydrographs for 36 randomly selected piezometer wells. The field examinations revealed that construction and stability of all piezometer footings was satisfactory, and verified that water levels and piezometer depths were within 10 percent or less of reported values at all wells. Evaluation of the water-level hydrographs indicated that ground-water levels fluctuated seasonally in all of the wells, with highs corresponding to peak stages of the Senegal River in October-November and lows corresponding to lowest stages of the river in May-June. Maximum annual fluctuations in ground-water levels in the 36 piezometers ranged from a few tenths of a meter to about 3 meters.

Hydraulic conductivities of the aquifers was computed from slug-injection test data previously collected by project personnel for 137 piezometers located in the lower Senegal River delta. These calculated values ranged from 1.0×10^{-3} centimeters per second at piezometers completed in medium- to fine-grained sand to 8.0×10^{-7} centimeters per second at those completed in silty clay or a combination of sand, silt, and clay.

The favorable results obtained from the evaluation of data for randomly selected piezometers in the network attest to the reliability of the piezometer installations and the operation of the network.

Because of the accurate and detailed information collected in Phase I, it would be appropriate to proceed with Phase II. The objectives of Phase II would be twofold: (1) a reevaluation of previous work in light of recently collected data, and (2) to provide a foundation for the

modeling effort. A formal report of the technical interpretation of the data is needed because without it, the data become less useful. The report would make the data meaningful and useful to the people of Senegal, to Organisation Pour La Mise en Valeur du Fleuve Senegal and the U.S. Agency for International Development, and to the international hydrologic community.

Additionally, an increased knowledge of the flow system could be gained by simulating the Senegal River valley system by use of an existing digital computer model for ground-water/surface-water flow Phase III. If accomplished, the work effort required for Phase III could provide significant contributions to education, technology transfer, and to applied research in hydrogeology, as well as to management of the water resources of the Senegal River valley.

REFERENCES

Audibert, M., and Filippi, C., 1984, Influence de la retenue de Diama sur la nappe salee dans le delta du fleuve--rapport d'expertise: unpublished report (84 AGE 037) from the Bureau de Recherches Geologiques et Minerves to the Organisation pour la Mise en Valeur du Fleuve Senegal, Orleans, France.

Ferris, J. G., and Knowles, D. B., 1963, The slug-injection test for estimating the coefficient of transmissibility of an aquifer, Methods of determining permeability, transmissivity, and drawdown, 1963: in U.S. Geological Survey Water-Supply Paper 1536-I, p. 299-304.

Ghislain de Marsily, 1986, Quantitative hydrogeology; Groundwater hydrology for engineers: Academic Press Inc., Harcourt Brace, Javanovich, Publishers, 440 p.

Illy, Paul, 1973, Etude hydrogeologique de la vallee du Fleuve Senegal: unpublished report (RAF 65/061) to the Project Hydro-Agricolo du Bassin du Fleuve Senegal, Dakar, Senegal.

Morris, D. A., and Johnson, A. I., 1966, Summary of hydrologic and physical properties of rock and soil materials, as analyzed by the hydrologic laboratory of the U.S. Geological Survey, 1948-60: U.S. Geological Survey Open-File Report 60, p. 15.