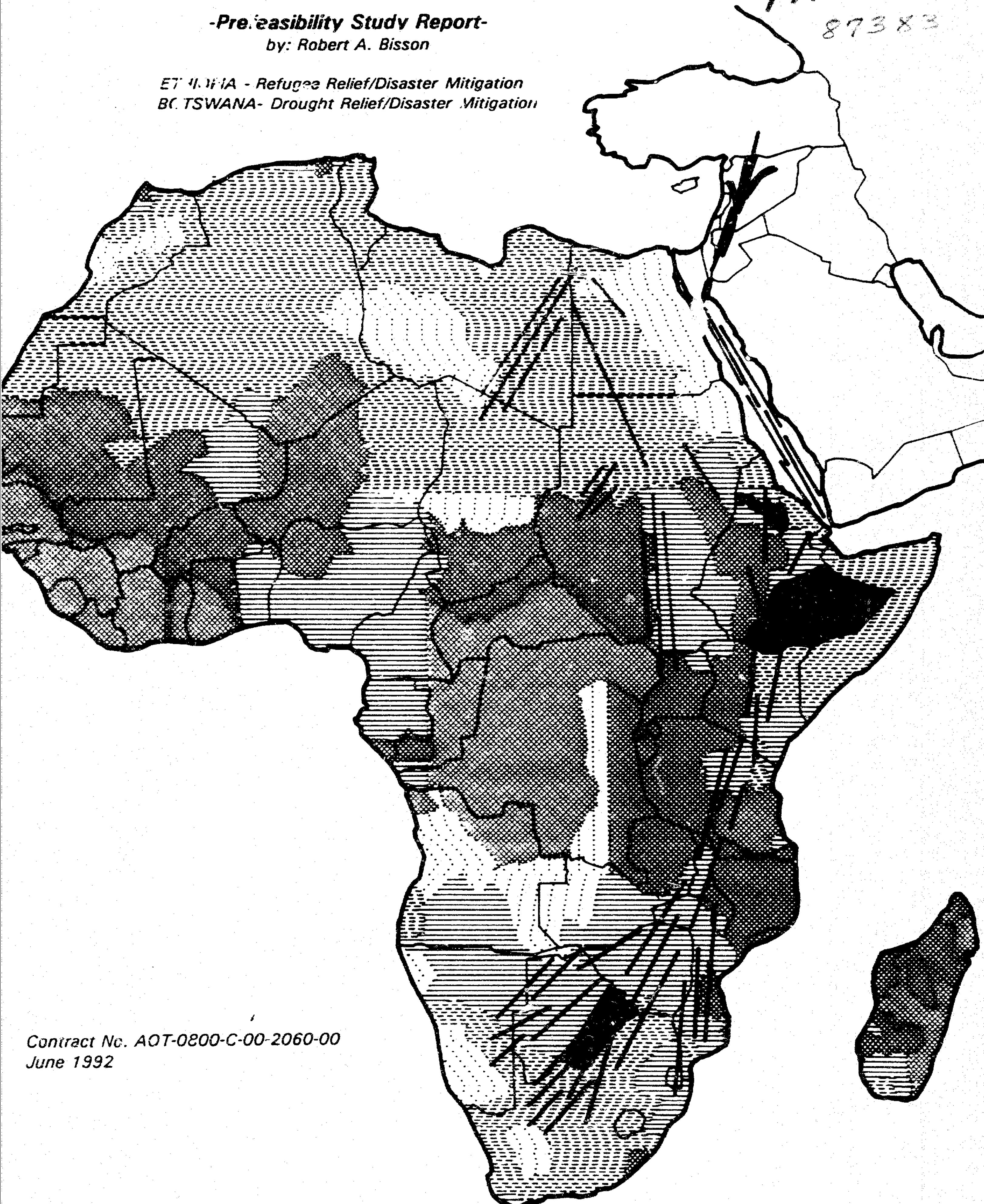
-Prefeasibility Study Report-

by: Robert A. Bisson

ETHIOPIA - Refugee Relief/Disaster Mitigation
BOTSWANA- Drought Relief/Disaster Mitigation



Contract No. AOT-0800-C-00-2060-00
June 1992

AFRICA

COMPOSITE MAP

- All irrigable soils in areas shown can be irrigated
- Water available for more than 50% of irrigable soil
- Water available for 10% to 50% of irrigable soil
- Water available for less than 10% of irrigable soil
- Insufficient water for irrigation

- ETHIOPIA TIGRAY REGION
- ETHIOPIA OGADEN REGION
- BOTSWANA EASTERN REGION

- Dead Sea Rift
- Nile Rift
- Red Sea Rift
- East Africa Rift
- South East Africa Rift
- South West Africa Rift

This map series is part of the Botswana and Ethiopia Megawatersheds pre-feasibility study written by Robert A. Bisson. The study goals include the demonstration to USAID, the governments of Botswana and Ethiopia, other african countries and international aid and development institutions of the critical nature of regional and national water resource management strategies in drought relief disaster mitigation and development planning. These strategies can be efficiently designed and implemented using a Geographic Information System (GIS).

Geographic Information Systems (GIS) is an information technology which stores, analyses, and displays both spatial and non-spatial data. It is a decision support system involving the integration of data in a problem-solving environment. This map represents one of the ways of displaying spatial and attribute data.

The Mercator projection was used for this map.

This map was produced for GIS demonstration purposes from Food and Agricultural Organization of the United Nations map 1986 and other maps. GIS analysis provided by PADCO under contract with Robert A. Bisson.

PADCO

June, 1992 V.Z.

MEGAWATERSHEDS IN ETHIOPIA AND BOTSWANA

-Prefeasibility Study Report-

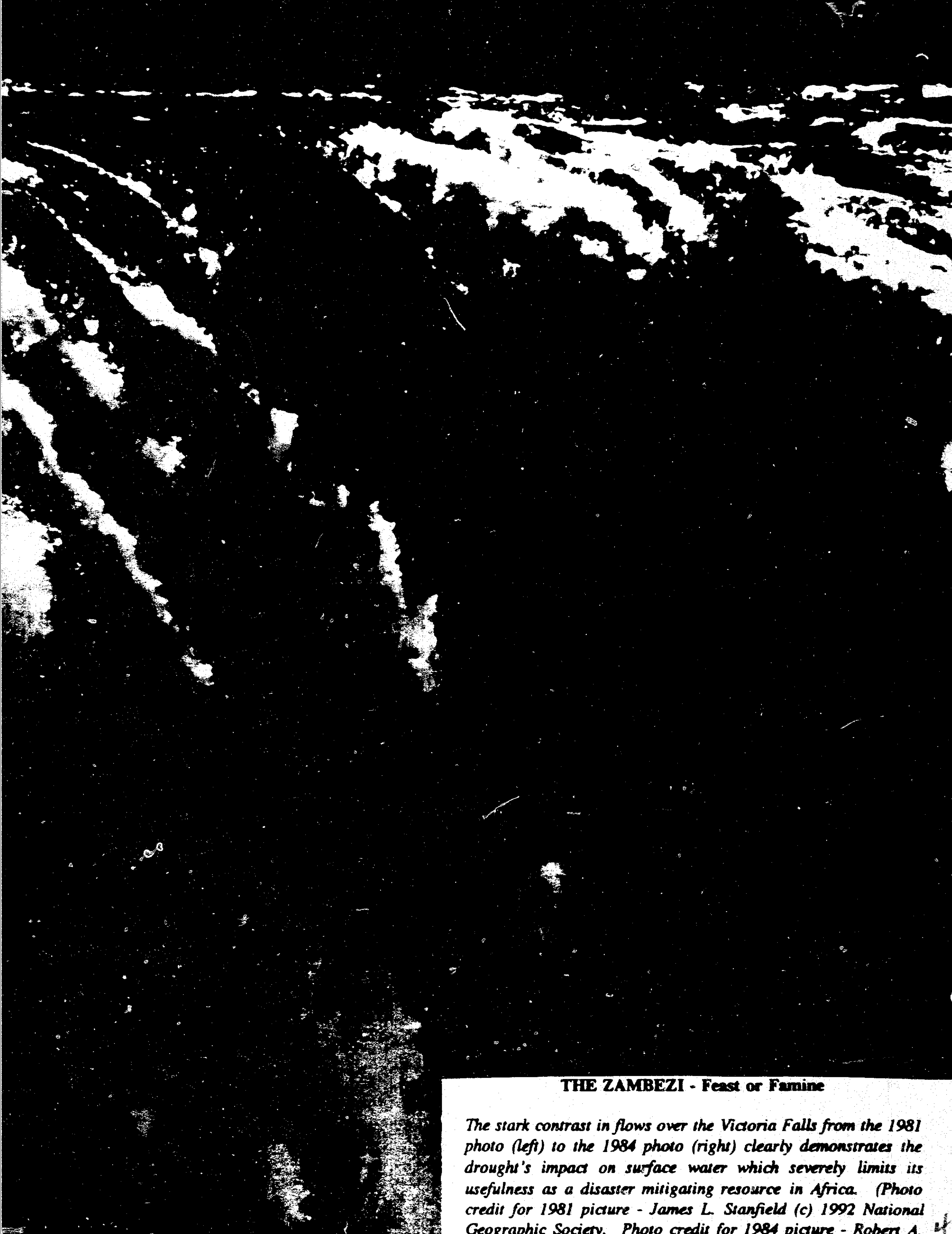
by: Robert A. Bisson

ETHIOPIA
Disaster Mitigation-
Refugee Water Supply Assistance

BOTSWANA
Disaster Mitigation-
Drought Relief

PIO/T No. 2681800

Contract No. AOT 0800 C 00 2060 00



THE ZAMBEZI - Feast or Famine

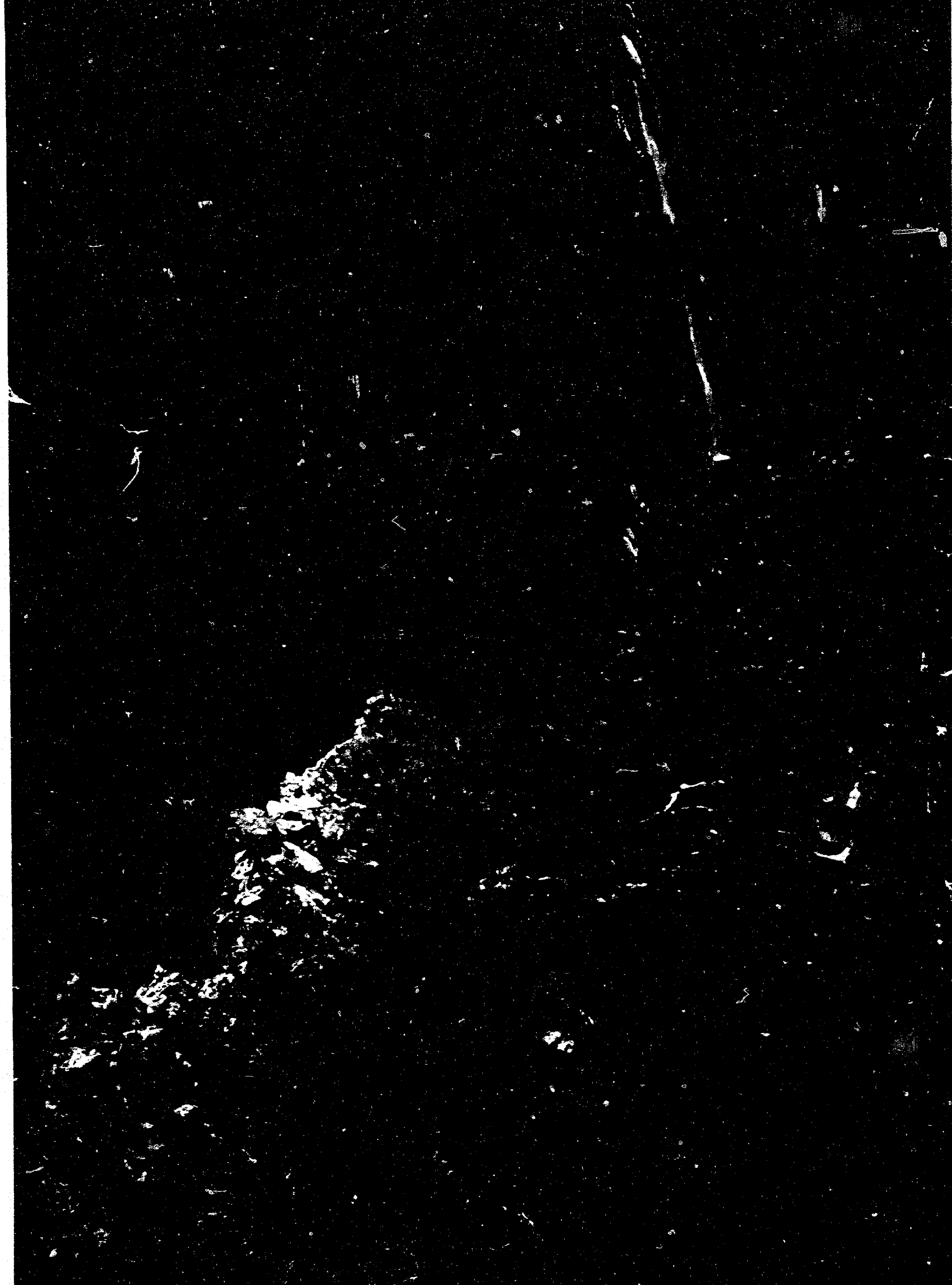
The stark contrast in flows over the Victoria Falls from the 1981 photo (left) to the 1984 photo (right) clearly demonstrates the drought's impact on surface water which severely limits its usefulness as a disaster mitigating resource in Africa. (Photo credit for 1981 picture - James L. Stanfield (c) 1992 National Geographic Society. Photo credit for 1984 picture - Robert A.

Southern Africa Rift - Controlled Water Resources

As seen from an AVHRR (Advanced Very High Resolution Radiometer)
September 7, 1985

Images from outer space often clearly depict the rift and related fault and fracture systems which control Africa's major and groundwater drainage. The photo is oriented north/south with the Okavango Delta clearly shown in the north-center, and the Cape of Good Hope located at the south-center. The Chobe and Zambezi Rivers can clearly be seen running parallel to the Okavango at the top portion of the photo. All three rivers intersect the African Rift system and are diverted by these structures.

The rift systems which pervade the continent and define its physiography also control Africa's most significant water resources - Groundwater in regional fractured rock systems may provide an environmentally realistic alternative to using surface and traditional alluvial sources in Africa's chronically drought affected areas.



Groundwater Megawatershed Exploration

As can be seen in this photo of a scuba diver swimming along a fractured rock aquifer several hundred feet underground in the state of Florida, vast quantities of fresh water can flow through fault-controlled cave systems in carbonate rocks. Large regions of Africa, including parts of Egypt, Ethiopia (most of the Ogaden and the SADCC states are underlain by similar fractured limestone rock units. (Photo by Wes C. Skiles)

MEGAWATERSHEDS IN ETHIOPIA AND BOTSWANA
TABLE OF CONTENTS

PHASE I

PHASE I

PREFEASIBILITY STUDY REPORT
MEGAWATERSHEDS IN ETHIOPIA AND BOTSWANA

Background and Problem

In recent times, predictable, recurring droughts induced famine and related disaster in Eastern and Southern Africa. International and bilateral donors, including the United States (US), have pumped billions of dollars into sometimes "band aid" solutions, which save some lives, but do little to break the cycle of expenditures and misery. Assistance efforts frequently promote donor-dependency among the aid recipients.

Many of the affected areas and populations lack basic development, such as transportation, food storage options, alternative income opportunities, medical services, physical security and potable water. When drought intensifies, significant dislocations of people occurs. Refugee camps spring up, often in very remote, hostile places where it is difficult to deliver and administer needed assistance. Water, food, shelter and medical supplies become critical support factors and major expense items. A "successful relief operation" can contain seeds of irony by creating "temporary" camps that may well outlast the conditions of the natural or man-made disaster. Competition between refugee camps and local populations for surrounding or imported resources can cause significant socioeconomic, environmental, and political disruption. In view of these chronic secondary problems associated with repeated "crisis management" methods to handle predictable problems of this nature, investments in disaster planning and mitigation efforts seem quite sensible.

Beyond drought or emergency scenarios, a number of African countries are struggling with "regular" development problems: urbanization, food production, environmental problems, expanding health and human services, employment, sharing natural resources between domestic livestock and wild life, etc. For example, in Southern Africa (also severely affected by the current drought), the World Bank and governments of Botswana and Zimbabwe have been considering different ways to ensure adequate supplies of water for their advancing economies. Because of the proximity of great rivers in the area, most attention has been given to schemes which divert and transport these surface supplies over considerable distances. Besides needing substantial funding (300 million to 500 million USD), and many years to implement, these projects are aimed at surface water resources that can be of no help during severe drought conditions. (See contrasting photographs of the Zambezi's sometimes great Victoria Falls in the front of this report.) In addition to posing large-scale environmental impacts, our experience elsewhere in Africa (the Nile River), the Middle East (the Jordan River) and the US (the Colorado River), strongly indicates that trying to divert a river like the Zambezi could be problematic if international riparian rights were not first negotiated with other countries like Angola, Zambia, Zimbabwe and Mozambique.

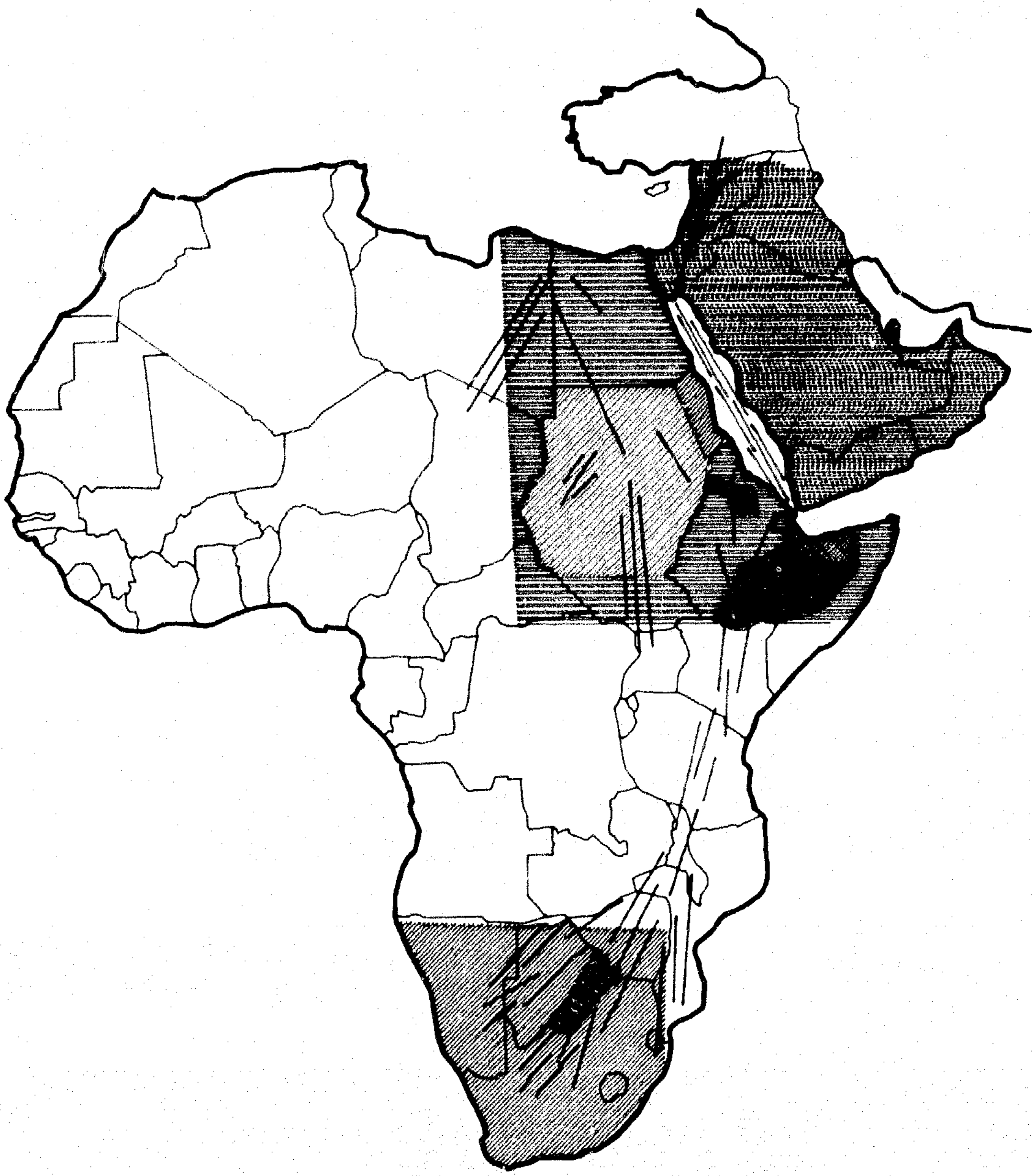
A Potential Water Alternative

Water is a critical determinant of health and economic well being, regardless of the stage of a country's development. The use of traditional technologies to impound or divert surface water, or drill shallow wells into alluvial aquifers have had limited success in arid regions, not only because they are very drought-sensitive, but also because they often impose a high cost to the local populations and burden governments with more debt than they can afford. In addition, delivering potable water meeting WHO standards is difficult to achieve or maintain in traditional surface and shallow well sources in Africa.

At the same time, the Great Rift systems of Africa, which are splitting the continent apart, have created groundwater environments which offer an alternative water resource opportunity (see cover map). These Rift systems and new exploration technology may lower development costs by greater than eighty percent, shrink development time frames (months in lieu of years) and pose far fewer environmental hazards. A typical fault-derived regional aquifer in a carbonate region (very common in Africa) is depicted from inside the bedrock in the photograph that follows this page. These resources are believed to be drought-resistant and possess substantial recharge potential over very large areas. In fact, tectonically-derived fractured bedrock "Megawatersheds" may underlie some of the most water-starved areas of Africa, from Egypt to Namibia (See cover photo and other enclosed enclosed and general illustration maps of geographic locales and history of related studies by Mr. Bisson, et al., 1983-92 as well as Appendix I -- "Megawatersheds" -- Exploration Model).

Study Activities and Conclusions

Based upon a combination of prior investigations and successful water development work in Africa, and recent work performed under this contract in the US and Africa, the contractor completed this prefeasibility study for employing proven US technology to estimate the potential fractured bedrock water resources in target areas of Ethiopia and Botswana.



MEGAWATERSHEDS OF AFRICA/MIDEAS

OVERLAY

(FOR ILLUSTRATION PURPOSES ONL

- Ethiopia Tigray region Bisson proposed USAID phase II project 1992
- Ethiopia Ogaden region Bisson proposed USAID phase II project 1992
- Botswana eastern region Bisson proposed USAID phase II project 1992
- Bisson USAID contract 1987-1989
- Bisson USAID contract 1987
- Africa Studies by Bisson's team as megawatershed research
- Bisson USAID contract 1983-1986
- Bisson contract with private company-priliminary exploration
- Mid-East studies megawatershed 1983-1992

- Dead Sea Rift
- Nile Rift
- Red Sea Rift
- East Africa Rift
- South East Africa Rift
- South West Africa Rift

Notes

1- Projection used for this map is Mercator projection

This map was digitized and produced for Robert A. Bisson by Planning and Development Collaborative International (PADCO)

June, 1992

In Ethiopia, based on prior successful water mapping by Mr. Bisson for United States Agency for International Development (USAID) in the Horn of Africa and the use of the same proprietary approach in solving refugee water problems, USAID agreed that Mr. Bisson should carry out a preliminary feasibility study. To assess the practical, near-term potential to improve water access for refugees and people in otherwise economically viable sections of the Ogaden and Eritrea (or other) regions and design a pilot water mapping/testing program (Phase II) to deal with the problem. An expanded understanding of water resources and the application of advanced well-siting and drilling techniques would increase the cost-effectiveness of refugee assistance and disaster mitigation programs.

Based upon prior investigations of the area by Mr. Bisson's team and new information gained during interviews with Ethiopian government officials and other experts inside Ethiopia and in the US, the Phase I team was able to answer several questions of feasibility, including promising target regions, time frames and costs for Phase II mapping and test drilling, test pumping, and the possibility for employing Geographic Information System (GIS) techniques to enhance local or national resource development planning.

In Botswana, a USAID review of Mr. Bisson's technical rationale for a Megawatershed underlying the Zambezi/Okavango region and the possibility that natural bedrock water storage and delivery systems may exist in other Southern African Development Coordination Conference (SADCC) states, resulted in a contract with Mr. Bisson for a preliminary feasibility study. The study goals, which have been met, included a survey of the Government of Botswana's water needs and interest in exploring alternatives, water development technologies and a pilot/test program, an evaluation of the practicality of the Megawatersheds concept, and the possible location and cost of a demonstration pilot program (Phase II, conceptual mapping and test drilling).

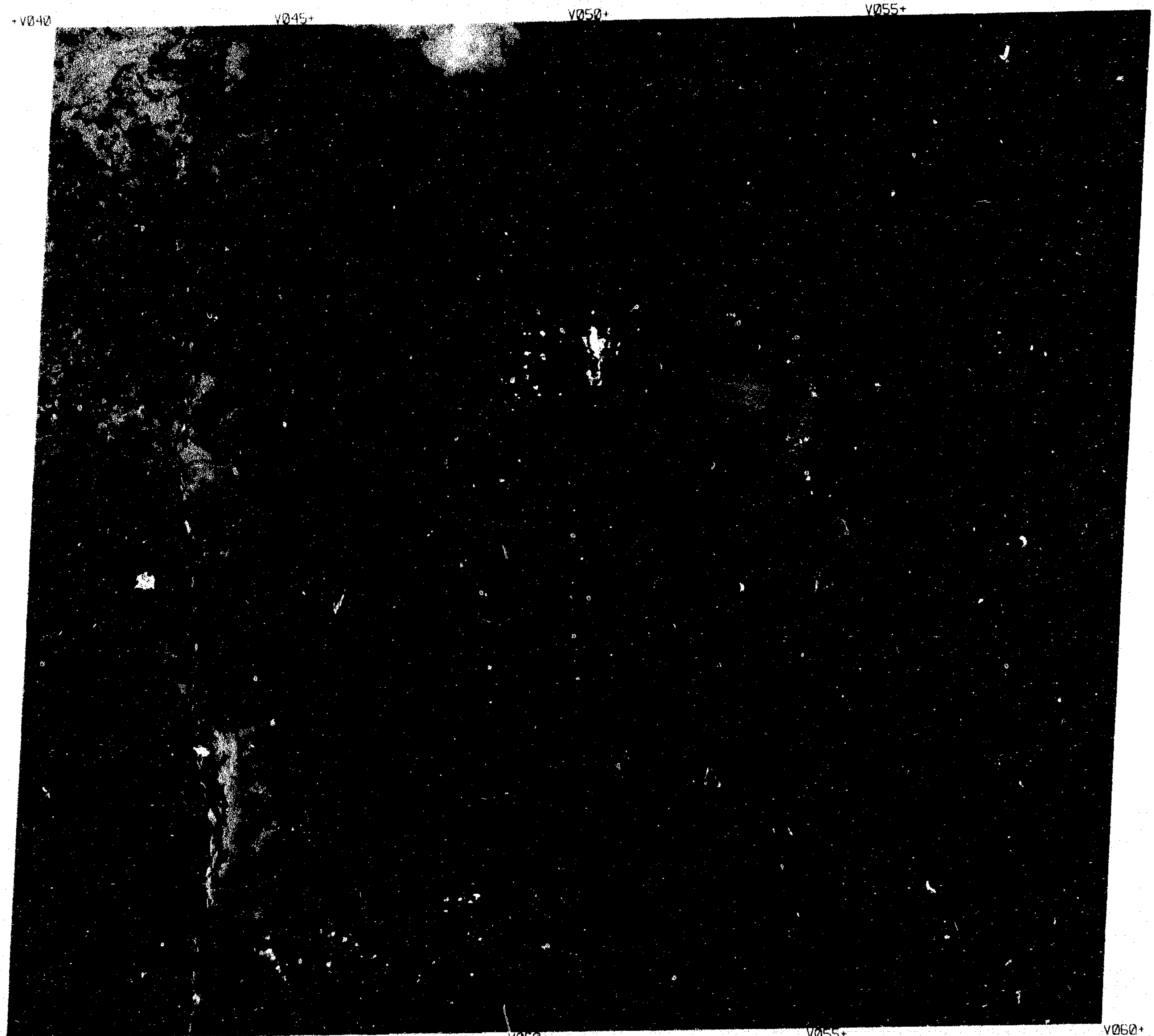
Mr. Bisson's overall conclusion in both countries is that the application of this refined US water exploration technology, and special mapping and drilling techniques, promise to be cost-effective alternatives to current water resource development. The recommended Phase II exploration and mapping activities can identify the best available sites for sustainable yields of high quality water from expertly drilled wells. In Ethiopia, the drilling of test wells would also hopefully result in high quality water supplies in proximity to refugee camps or populations most affected by the drought conditions.

The Phase II demonstration activities should also help calibrate the Megawatershed Model at both ends of the Africa Rift System, further expanding knowledge about the phenomenon and exploration concept.

Sabe River Portion of the Southeast Africa Rift System

The Landsat image on the facing page illustrates a fault/fracture orientation related to the Africa Rift controls of the Sabe river basin. Mountain rainfall in eastern Zimbabwe offers an extensive potential groundwater recharge area for a Sabe River Megawatershed. Further investigations in the SADCC region will reveal other Rift associated fractured rock hydrologic regimes with similar agricultural, famine mitigation and industrial implications.

00350-115



25JUL79 C S20 09/E032 57 USGS-EDC N S20 10/E032 59 M R SUN EL31 A049 S3H-CP-N L2 NASA LANDSAT E-21645-06592-3

180 D 074

However, because the Megawatershed Model could: (1) represent major additions to regions' recoverable water resources, and (2) provide sustainable volumes of water in new locations, consideration should be given to the socio-economic and environmental impacts of additional water. Since such might also include, in some areas, a multi-country tapping of hydraulically interconnected systems, over-arching policies will need to be formed to intelligently manage what could be a resource of political note as well as strategic comparative advantage. Donor agencies and participating governments would do well to begin assessing such extra-regional implications in parallel with the recommended Phase II demonstration effort.

Notwithstanding these concerns Phase II work should start immediately to help the recipient agencies overcome drought problems they are now facing, as well as develop strategic water resource maps to support disaster mitigation and future development activities.

Goals For Phase II

Based on the preliminary feasibility study findings, the overall objectives of the Phase II Megawatersheds project are described below.

1. To provide proof of the existence and accessibility of major, renewable fresh water resources of a regional nature to Ethiopia's and Botswana's political leaderships;

2. To provide near-term relief to refugees and other victims of drought in Ethiopia and Botswana.

3. To mitigate future potential disasters of a naturally recurring nature by providing permanent, sustainable fresh water sources at strategically located sites.

4. To offer solid evidence of economically practical fresh water sources to the private sector, who might then work with government planners to invest private capital into these countries, in mining, food production, agro-industry, manufacturing, transportation, etc., to enhance local and regional growth. This readily translates to expanded employment and increased economic opportunity.

5. To provide the same "proof of concept" to various international institutions, including USAID, UNICEF, UNHCR, World Bank and others committed to saving lives, reducing human suffering, preventing crises and encouraging social and economic self-sufficiency, whose program interventions have frequently been stymied by the chronic lack of dependable fresh water.

The project's Phase II results also will hopefully provide sufficient evidence to induce in these institutions a "paradigm shift" regarding local or macro-regional water policies and projects:

<u>from</u> high price "big bang" surface water schemes (that often have adverse political, ecological and social impacts) and marginal alluvial borehole drilling exercises,

<u>to</u> reliable, practical groundwater development strategies based on new technologies, which lesser developed countries can better afford to undertake.

PHASE II

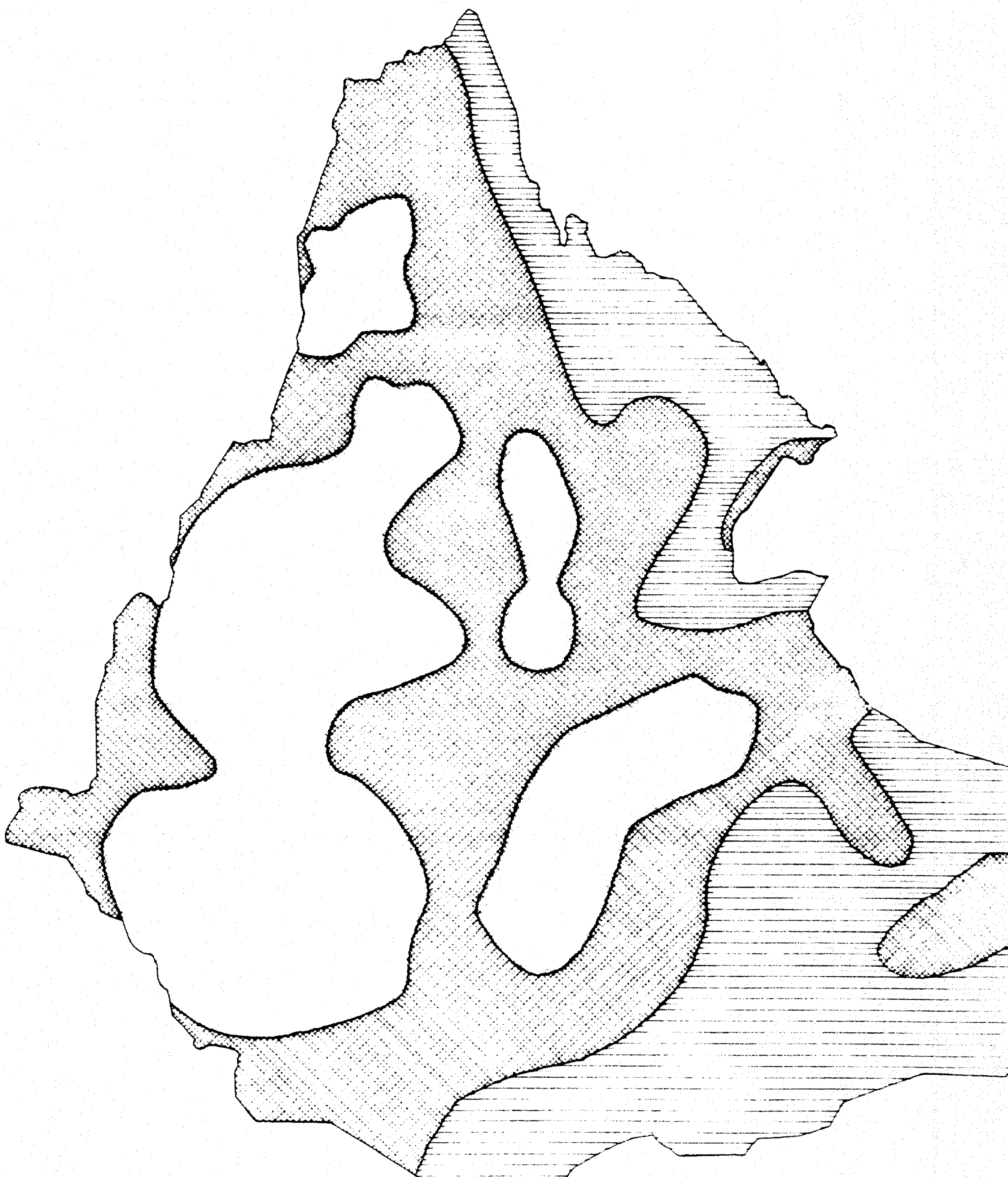
ETHIOPIA ACTION PLAN

In-Country Evaluation

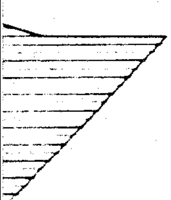
Ethiopia has a critical shortage of adequate water supplies in most regions of the country. Years of civil strife have left a damaged infrastructure, a faltering economy, and, in many areas, significant displaced or refugee populations. Political and ethnic fighting in neighboring countries have added thousands of refugees. Better, less expensive sources of water are badly needed for the refugee camps. Current drought conditions have further disrupted food production and employment activities, making the restoration of minimal water supplies an important ingredient in a general recovery program, which would also mitigate the impact of future civil or natural calamities.

During the prefeasibility study, Mr. Bisson's team held discussions and meetings with local government officials, UNICEF personnel, other coordinating agents and representatives of the private sector. These meetings revealed an acute need for better well-siting technology, improved drilling hardware and methods, and an accurate regional map of potable groundwater resources to support refugee relief programs and recovery planning by public, private and donor community officials. While significant funds have been expended over decades in the search for high quality groundwater, success rates have been disappointing. The study team is convinced that a practical, accurate water source map could be completed and new water sources located near refugee concentrations. The basis for this belief is the extensive amount of team experience on the ground in adjacent regions of Sudan and Ethiopia, as well as evaluation of data collected by Mr. Bisson in Ethiopia in the 1980's. A concerted effort by Mr. Bisson's team in 1989 lead to the creation of a preliminary national groundwater "favorable regions" map of Ethiopia. Immediately thereafter, Mr. Bisson alerted the Office of Foreign Disaster Assistance at USAID regarding the practical opportunity for major new groundwater supply development in Ethiopia. A copy of this unique map is contained in this report on the following page.

An excellent contrast to Mr. Bisson's "favorable regions" map, which reflects secondary, fractured rock, permeability is the unpublished working map of water potential (following) based on comprehensive evaluation of existing literature by the USSR team. sent Mr. Bisson in 1990 as part of a would-be collaborative effort in the Ogaden, which never transpired.



AQUIFER YIELD CHARACTERISITICS FROM SECONDARY (FRACTURE) PERMEABILITY IN THE ETHIOPIA REGION



Q > 5400 cubic meter/day

Q > 2700 cubic meter/day

Q > 1000 cubic meter/day

This map series is part of the Botswana and Ethiopia Megawatersheds pre-feasibility study written by Robert A. Bisson. The study goals include the demonstration to USAID, the governments of Botswana and Ethiopia, other african countries and international aid and development institutions of the critical nature of regional and national water resource management strategies in drought relief disaster mitigation and development planning. These strategies can be efficiently designed and implemented using a Geographic Information System (GIS).

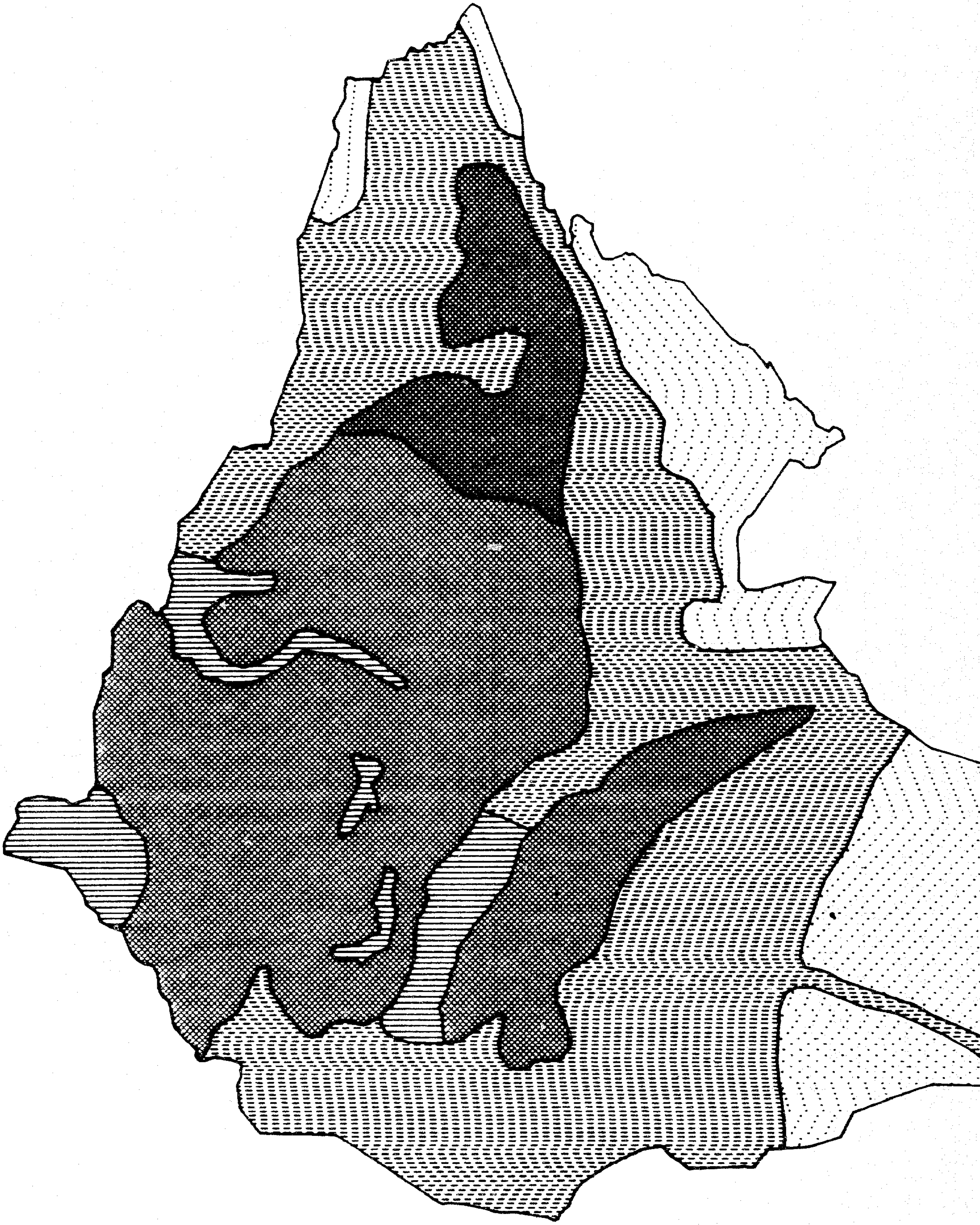
Geographic Information Systems (GIS) is an information technology which stores, analyses, and displays both spatial and non-spatial data. It is a decision support system involving the integration of data in a problem-solving environment. This map represents one of the ways of displaying spatial and attribute data.

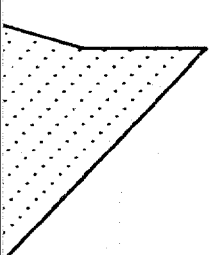
The Mercator projection was used for this map.

This map was produced for GIS demonstration purposes from exploration mapping and USAID water development project 1984-1990 map. GIS analysis provided by PADCO under contract with Robert A. Bisson.

PADCO
GIS services

June, 1992 V.I.





MAJOR WATER RESOURCE REGIONS

IN THE ETHIOPIA REGION

- Widespread and moderate to large quantities of surface and or ground water. Good chemical quality
- Widespread and moderate to low quantities of surface and or ground water. Good to fair chemical qaulity
- Widespread and moderate to large quantities of surface and or ground water. Variable chemical qaulity
- Localized and moderate to large quantities of groundwater specially along valleys. Fair to poor chemical quality
- Main problem areas. Areas of high salinity of natural water

This map series is part of the Botswana and Ethiopia Megawatersheds pre-feasibility study written by Robert A. Bisson. The study goals include the demonstration to USAID, the governments of Botswana and Ethiopia, other african countries and international aid and development institutions of the critical nature of regional and national water resource management strategies in drought relief disaster mitigation and development planning. These strategies can be efficiently designed and implemented using a Geographic Information System (GIS).

Geographic Information Systems (GIS) is an information technology which stores, analyses, and displays both spatial and non-spatial data. It is a decision support system involving the integration of data in a problem-solving environment. This map represents one of the ways of displaying spatial and attribute data.

The Mercator projection was used for this map.

This map was produced for GIS demonstration purposes. It was provided by GEOSOFT, INC. Vienna, Austria. GIS analysis provided by PADCO under contract with Robert A. Bisson.

PADCO

June, 1992 V.Z.

In addition, appropriate drilling equipment and methods would greatly increase the percentage of wells completed and enhance their water yields (see Appendix III).

While the proposed Phase II program is relevant in most of Ethiopia, political security and assistance priorities reinforce the team's conclusion that initial efforts should be focused on refugee relief/disaster mitigation in the Ogaden and disaster mitigation/development planning in Tigray. Initially working in two areas would help confirm the relevance of the Megawatershed model for future regional or national level planning.

Based upon these discussions, the team concluded that Tigray Province and the Ogaden region would receive the most near-term benefit from the proposed Ethiopia program. Once the exploration model has been verified in Tigray Province and the Ogaden, the team could assist local officials, USAID, and other agencies in developing a program for expanding the water exploration and special drilling technology to other areas as an element of their strategic economic recovery plan for Ethiopia.

Study Region: Tigray

While the team's original intention was to examine Eritrea as a likely target region to meet Phase II goals, early results of the field trip indicated that this was not practical. Eritrea has water potential but couldn't fit the proposal's schedule because there is no longer a functioning coordination of activities or ongoing communications between the Ethiopian Government and the newly-formed Eritrean government. Tigray Province was chosen to replace Eritrea because: (1) the region is in a severe drought; (2) it has been identified as one of the most war-devastated areas of Ethiopia; (3) much groundwork has already been accomplished by UNICEF agents to identify and rank water supply needs here; and (4) it is considered to be politically stable. Consequently, short and longer-term water development efforts in Tigray would have the best chance of generating permanent benefit.

During our fact-finding investigations in Ethiopia we met with Tigrayan officials in Addis Ababa and with regional and local administrators and relief agents in Tigray.

According to these sources, groundwater exploration efforts in Tigray are very much needed for immediate refugee and disaster relief at the village level, for short and long term refugee resettlement, and for longer term strategic planning and economic development. Efforts are currently underway through UNICEF to assist in the drilling of village water wells. Unfortunately, logistical and political constraints have delayed this project. The Tigray Development Authority (TDA) is now undertaking a plan for the procurement of funding for a wide variety of services for the region.

Tigrayan development authority agents, local administrators and relief agency personnel revealed the following needs components:

Strategic Groundwater Resources Mapping and Well Site Identification

Severe regional drought has combined with a debilitating seventeen year war and the massive influx of refugees in Tigray province to undermine the economic, food and health base of the region. Shortages of food and water occur region-wide. The provision of emergency water supplies to villages or at critical waypoints is of utmost concern at present.

UNICEF has designed a comprehensive plan to identify the most critical areas of need and has just completed a region-wide survey of the province's villages, clearly identifying local water needs. UNICEF and other agency officials have expressed a desire to use Mr. Bisson's proprietary groundwater mapping and exploration technologies to assist in the location of water wells for villagers and small village-level food production and employment projects.

In accordance with the unsolicited proposals written by Mr. Bisson in 1991, he recommends using the same successful water exploration technology and experienced core team, contracted earlier by USAID in adjacent Somalia and Sudan. During the Phase II mapping program, a wide variety of existing data bases and specialized methods of interpreting satellite imagery and photography would be used to identify favorable areas for groundwater development. Air and ground-based geologic and geophysical surveys will also be conducted and all information input into a geographic information system (GIS) where further analytical functions will be performed by the team. "Hard" map and computer-compatible products of resulting water target areas would be generated as part of the final reporting process to USAID and/or the recipients.

Test Drilling and Equipment Procurement

The drilling rigs and associated equipment currently available in Ethiopia are limited in capability to drill through fractured rock, especially if the fractures produce large volumes of water. Since the goal of test drilling is to access and then test an acquifer's capacity to deliver sustainable quantities of fresh water to a correctly constructed well, this goal cannot be achieved unless specialized equipment and methods are employed during the drilling and well completion process (see Appendix III). As will be described later in this report, very large sums of money and time have been lost in Ethiopia emergency water projects due to inappropriate drilling technologies.

As in prior projects for USAID in Somalia and Sudan, Mr. Bisson's team will specify necessary equipment and supply it to the Ethiopian drilling teams, along with appropriate, on-site training in high-yield, fractured rock aquifer drilling methods Appendix III of this report contains equipment specifications from Mr. Bisson's Somalia Project.

Special Geographic Information System Procurement and Training

Currently the Tigray region has no mechanism for assembling and storing a wide variety of technical data relating to its economic, mineral and village resource base. An integral component of the exploration methodology the team would employ to evaluate and assess groundwater potential is a personal computer based geographic information system (GIS). This system enables users to input and manipulate a large volume of information from a variety of different sources to be compiled in either screen or map format for interpretation or display.

In addition to map products and training for Ethiopian water officials, it would be very beneficial to optimize ongoing famine relief and follow-through capabilities in Ethiopia by installing a GIS working database and Comsat (or equivalent) datalink system in-country immediately. This would facilitate the input and processing of local data during the construction of the water map and better assure follow through by local experts after Phase II completion. A trainer would be provided to insure that in-country experts were thoroughly familiarized with the system, which would be configured to operate in remote environments and would be equipped with spare parts and access to technical support via Comsat link.

Tigrayan officials, familiar with GIS and our proposed use of this system for the water exploration project, requested that the project's PC-based GIS software and compatible hardware be located in Tigray so that the Province's resource database can be established and maintained and in-country expertise can be gained for the future planning and development of the province.

Project Activities and Schedule

Mobilization to perform water exploration can be accomplished within fifteen days of execution of contract.

Mr. Bisson and his team would perform immediate follow up work in-country to secure commitments for manpower, rigs and equipment, obtain technical data existing only in Ethiopia, arrange for in-country transportation and fuel, procure shipping/customs clearances for equipment and continue liaison with government and relief agencies.

Test drilling at the First Priority Target Areas can begin within ninety to one hundred and twenty days of contract commitment. The ensuing drilling and testing program is designed to run for three to six months and to overlap with the mapping program.

The strategic water map would become a "working tool" within two months (with initial test drilling sites identified and mobilization of Ethiopian drilling rigs initiated) and could be completed within six to seven months of project commencement. Simultaneously, ongoing exploration and the refinement of the water resources map would be accomplished by Mr. Bisson's team and in-country personnel trained for the project.

Study Region: Ogaden

The Ogaden region of Ethiopia is an area where water supply development is most needed to support the refugee population. As reported during our visit, dozens of people were dying every day in Ogaden area refugee camps due to a lack of food and water. Just over the border in Kenya, even more famine victims were perishing.

Rival tribal factions and bandits have de-stabilized the area, making travel and relief work unsafe. Several relief workers had been killed. Relief shipments were being ferried via Hercules transport planes to the region. The food/water distribution network is, however, tenuous and often illogical and short-sighted. For example, in the northern Ogaden, UNHCR has for several years trucked water each day from a groundwater source to refugee camps some seventy kilometers away. The monthly cost for these services reportedly varied from 250,000 to 1,000,000 USD. The decision to supply these camps in this manner, rather than to drill and permanently equip water supply wells in the productive Jurassic limestone aquifers adjacent to the camps, has resulted in the spending of tens of millions of "band aid" dollars rather than solving the basic supply problem.

Based on prior water exploration and drilling results by Mr. Bisson's team in nearby areas of Somalia under USAID contract in 1986, (see photo - following page and Appendix II) a similar exploration and test well program carried out in Ethiopia with UNHCR funding equal to the trucking project could have provided permanent wells for all of the existing refugee camps in the Ogaden and the identification of additional strategic water resources, with sufficient funds left over to locate, drill, equip and maintain dozens of wells in areas which are critical for the long-term stability of the region. (The total cost for mapping and drilling of five test wells in the Somalia/Ogaden by Mr. Bisson's team was less than two million dollars. These small test wells produced more than 1.5 million gallons per day of fresh water. See Appendix II - Somalia Test Well Results).

Another unfortunate example of the shortcomings of traditional exploration and drilling approaches occurred in 1985-86 in Somalia in similar geologic structures. Drillers working for UNICEF in the same region as Mr. Bisson's team, sited and drilling four dry holes which cost a month each to drill. The UNICEF team then spent over a year and 1,000,000 USD to drill a single borehole to three hundred meters in what appeared to be a productive aquifer. Unfortunately, it failed due to inappropriate drilling technology and equipment. There is no need for these high cost disappointments (in dollars and human suffering) to reoccur, given the advances in water exploration and drilling techniques already proven in the same region under USAID funding.


COASTAL PLAIN AND PIEDMONT

During the preliminary feasibility study, in-depth discussions with UNICEF and Government of Ethiopia (GOE) personnel involved in the relief efforts in the Ogaden resulted in the following recommended actions which address major concerns of water for refugees and long-term regional stability:

1. Use of USAID-proven water exploration program to evaluate and rank water resource occurrence in the Ogaden, with special emphasis on the identification of "high need" areas for refugee relief and disaster prevention;

2. "Upgrading" of existing (or procurement of new) drilling hardware; procurement of drilling materials, and training of personnel, for the construction of water wells in "critical need" areas;

3. Test drilling, well development, and pump testing two sites within each of several target areas in the Ogaden;

4. Installation and testing of pumping equipment; and training for and continued maintenance of pumping equipment;

5. Placing test well water "on-stream" for immediate refugee and drought relief; and

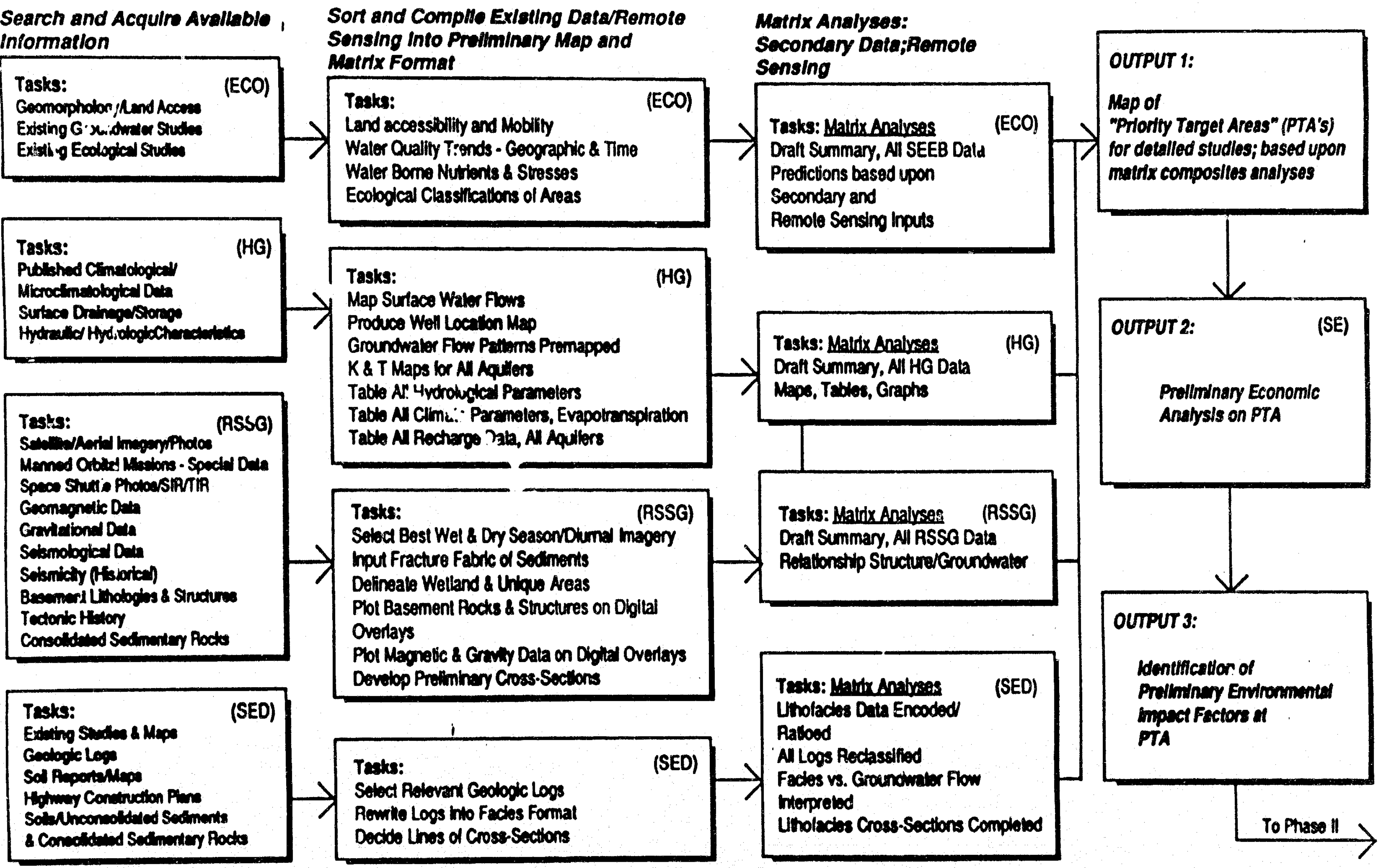
6. Transfer to Ethiopian/UN teams of all strategic maps, models and test results with appropriate training.

Special emphasis will be placed upon the standardization of materials and equipment for the project to insure that the training received by personnel continues to be of value in future projects.

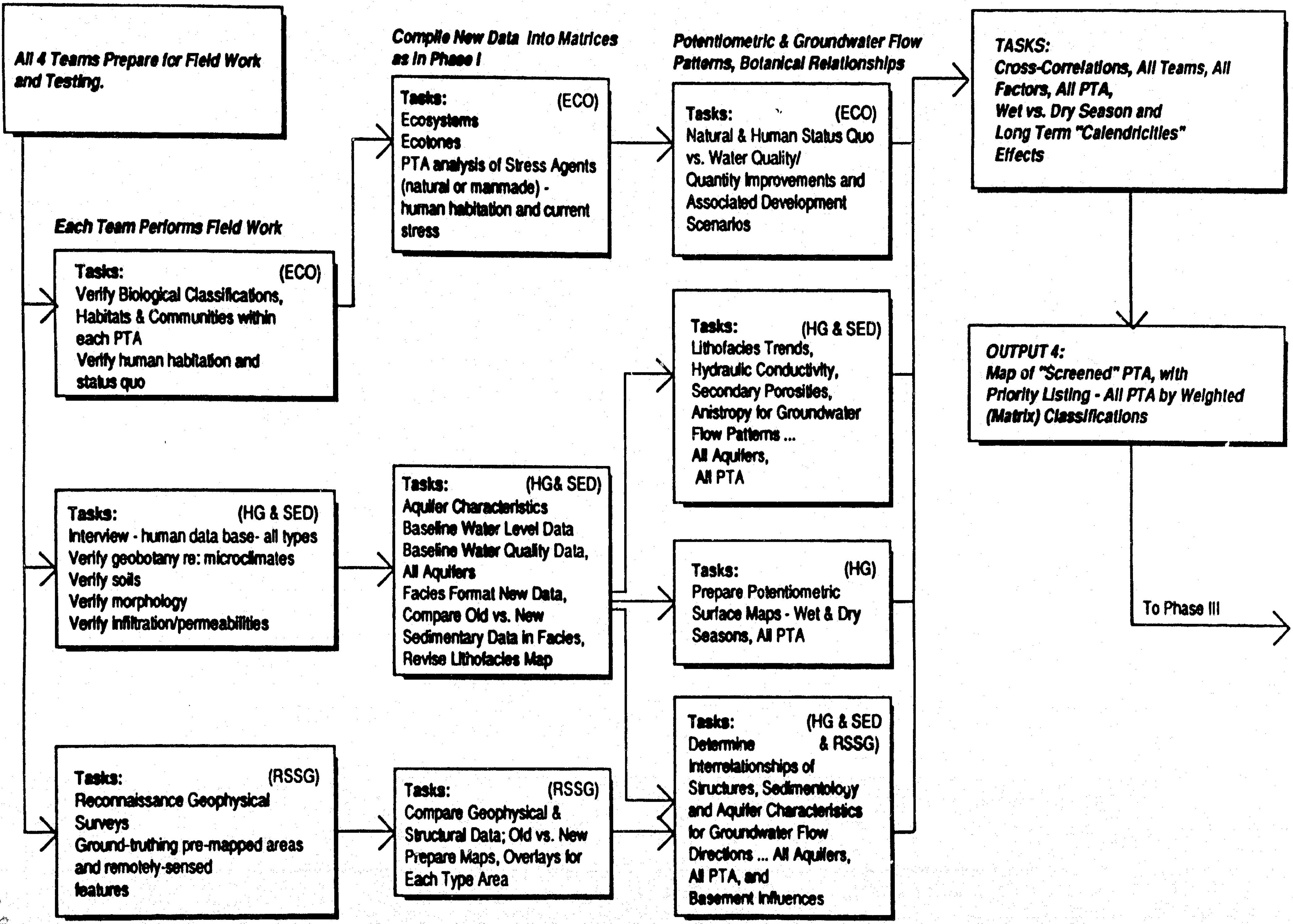
Strategic Groundwater Resources Mapping and Well Site Identification

The first element of the plan involves the generation of a preliminary strategic water map and subsequent identification of test well sites, using the same type of imaging, GIS interpretation and assessment processes described for the Tigray province program. Areas of need (Primary Target Areas) would be defined early on in the proposed exploration program by UNICEF and GOE experts, with special emphasis placed upon the discovery of high volume, fresh water sources proximal to these areas. The first goals of the draft strategic water map will be to identify target areas with high water potential which correspond to UNICEF/GOE priorities. If well sites and their priorities coincide, we believe UNICEF would be willing to drill the

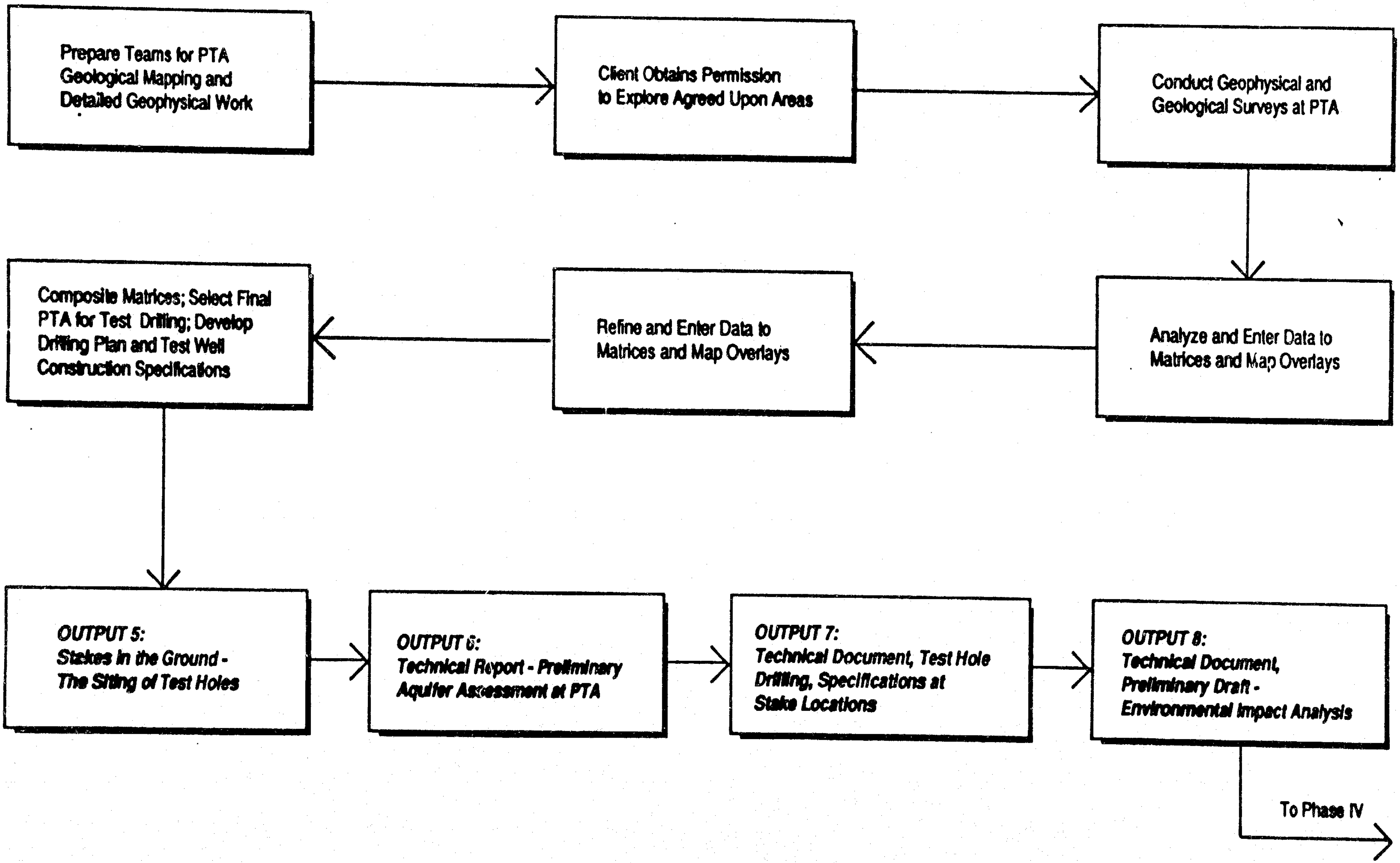
PHASE I - DATA ACQUISITION, COMPILATION, REVIEW, SYNTHESIS, AND INTERPRETATION OF ALL AVAILABLE INFORMATION



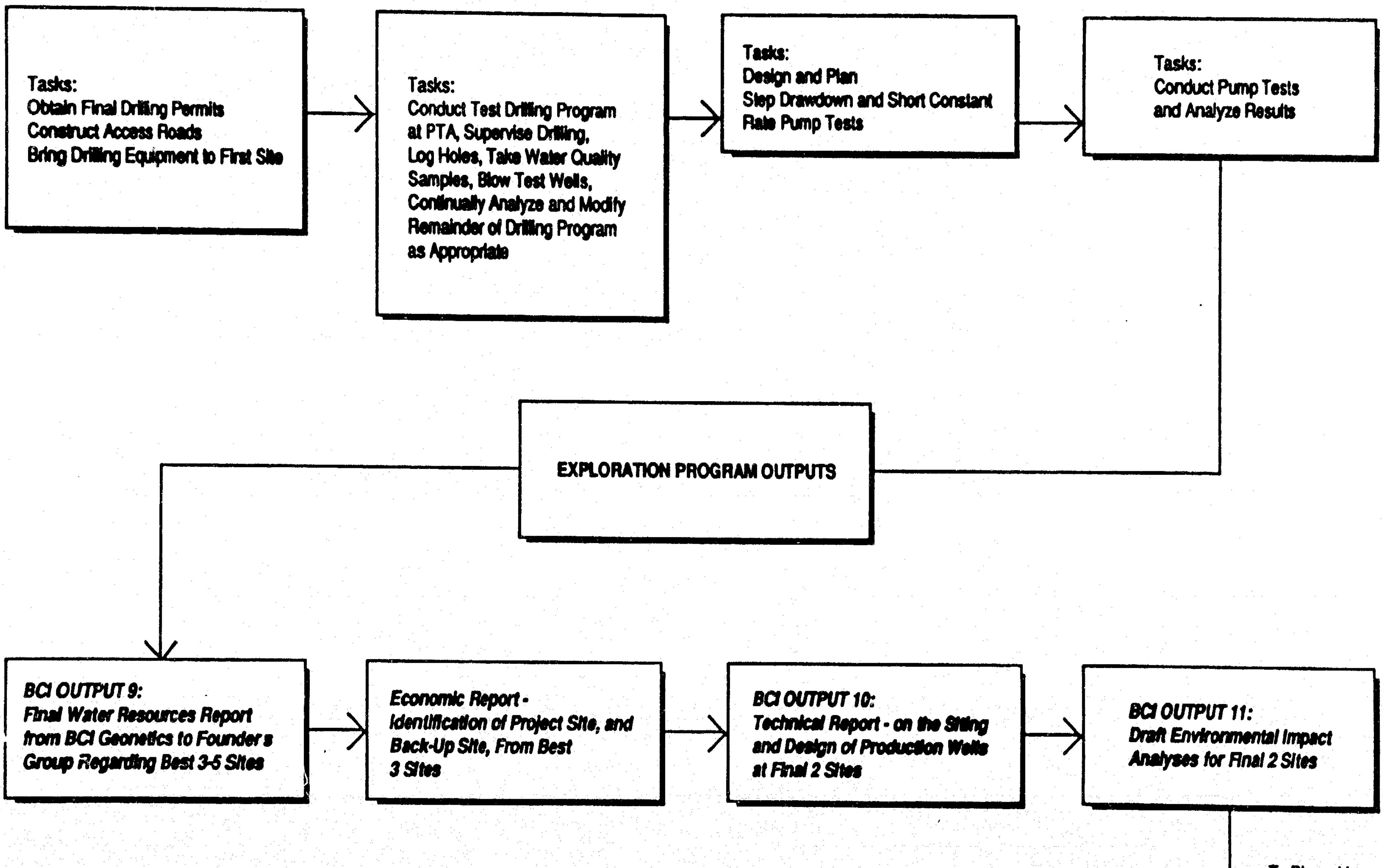
PHASE II - FIELD RECONNAISSANCE OF DESIGNATED "PRIORITY TARGET AREAS" (PTA)



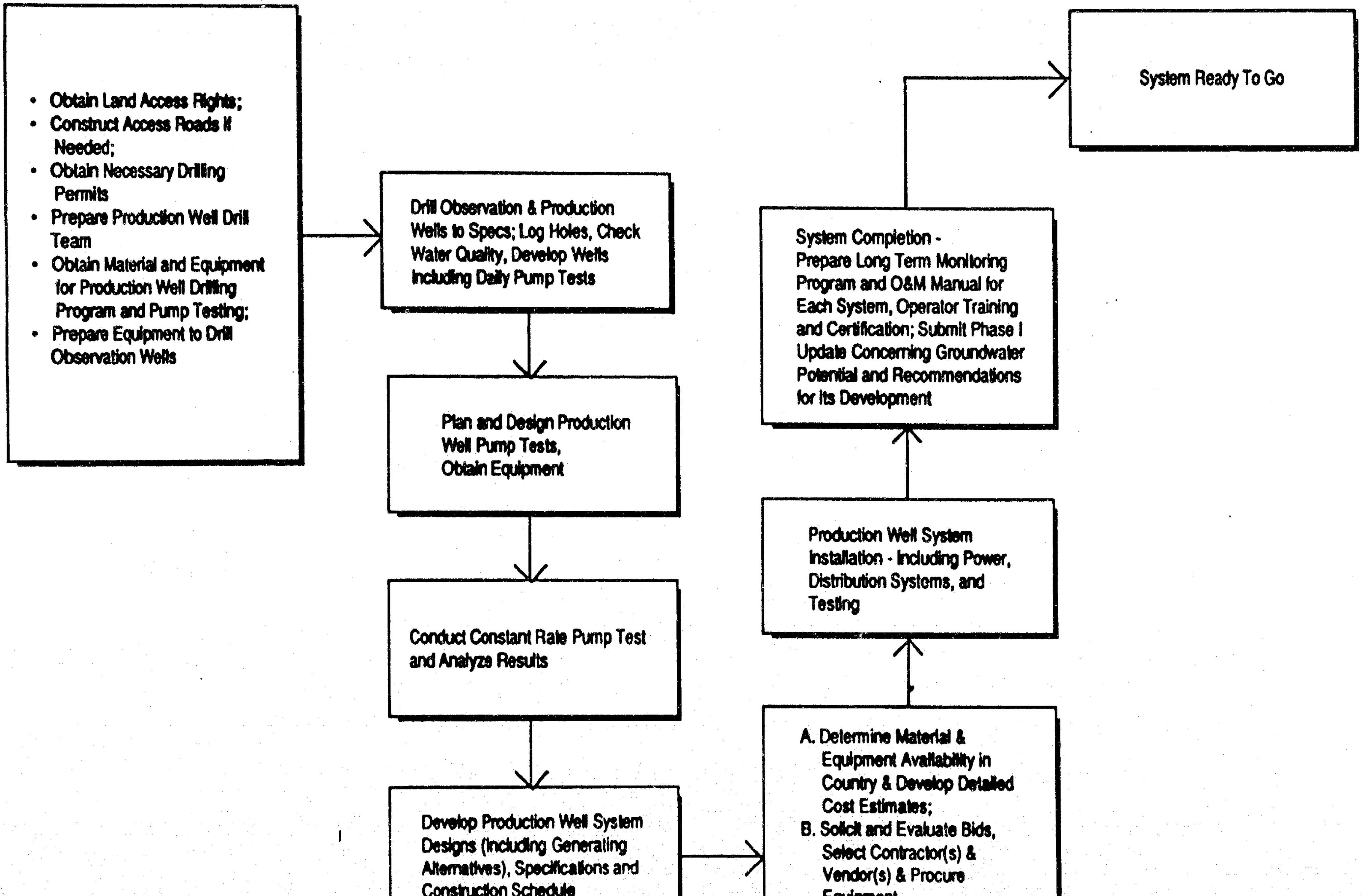
PHASE III - HIGH-RESOLUTION MAPPING - LOCATING OF TEST WELLS



PHASE IV - TEST HOLE DRILLING AND PUMPING TESTS

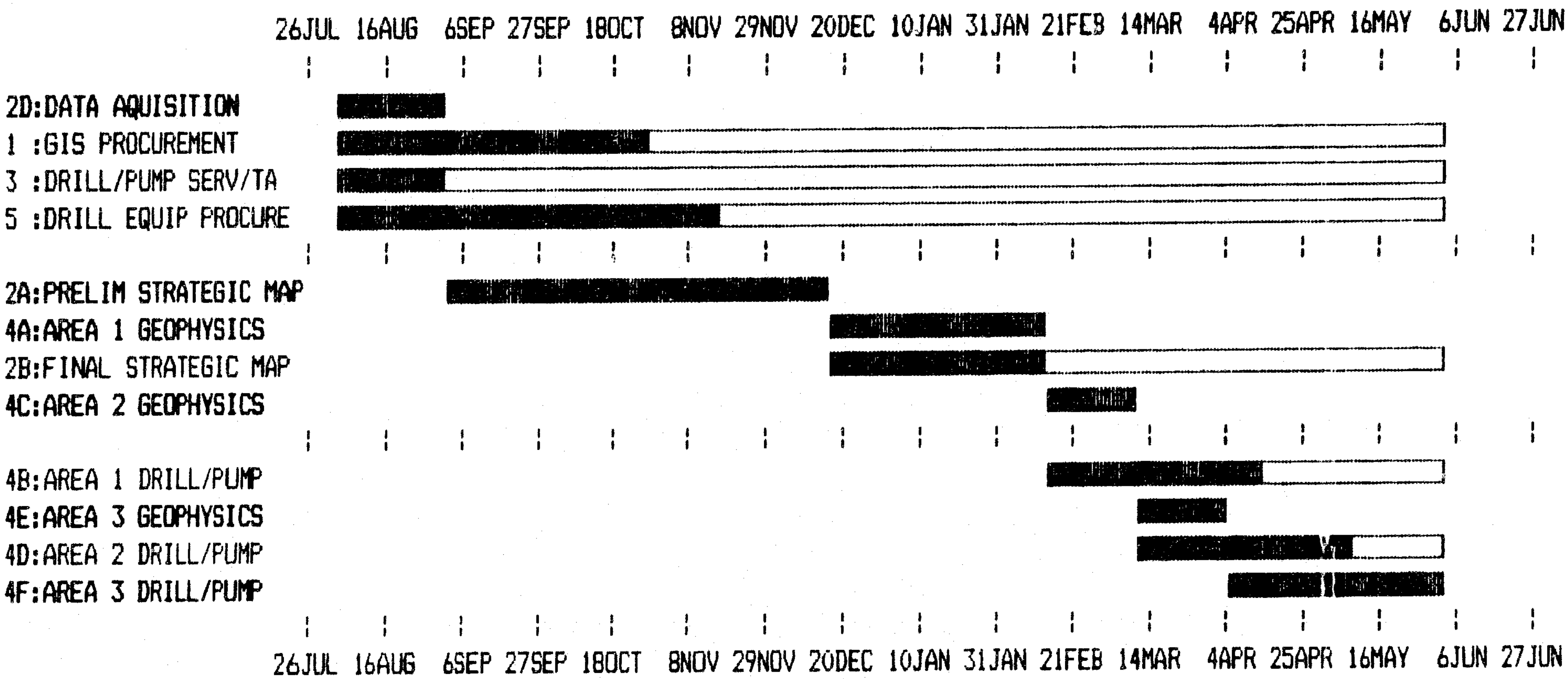


(FUTURE) PHASE V - PILOT DEVELOPMENT PROJECT: PRODUCTION WELL SYSTEM INSTALLATION



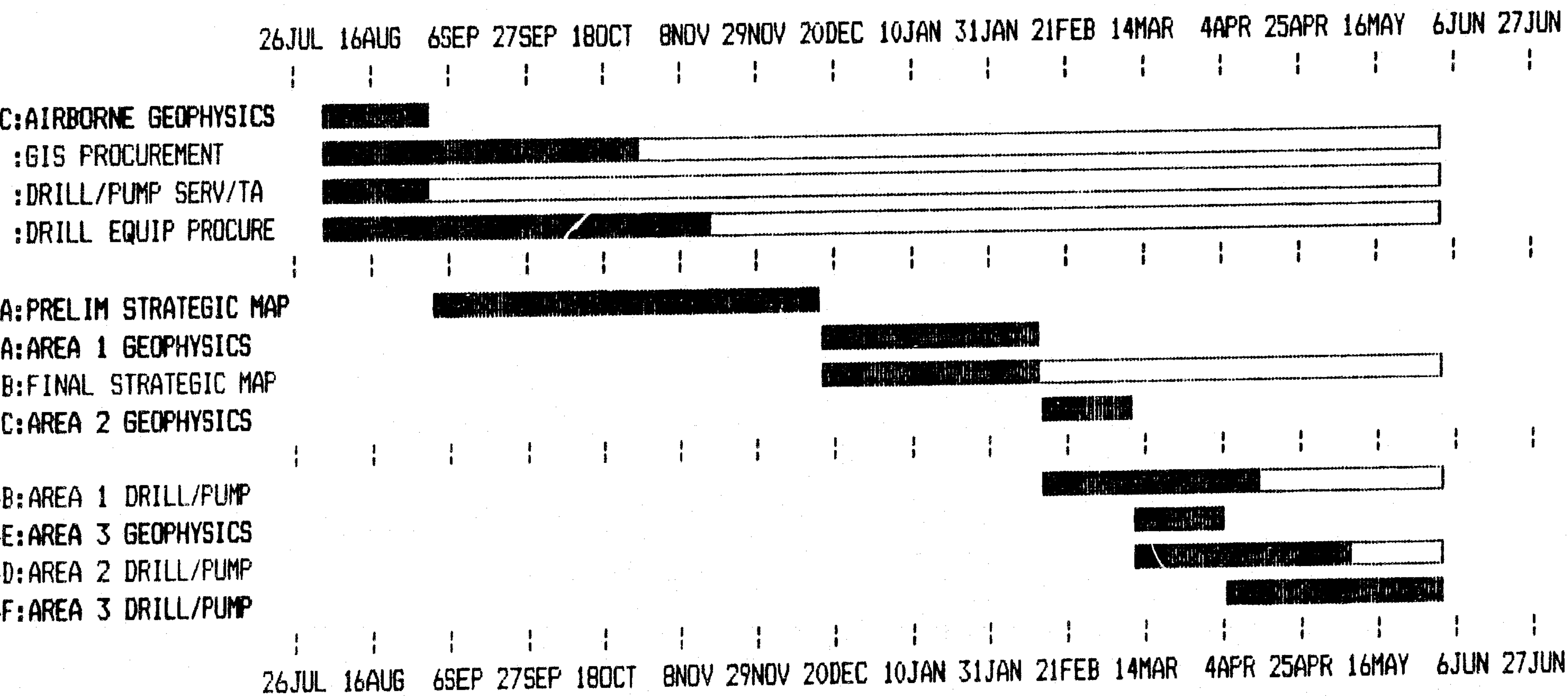
TIGRAY EXPLORATION

10:20 ON 06/25/92 PROJECT STARTS ON 1AUG92 PAGE 1



OGADEN EXPLORATION

1:01 ON 06/25/92 PROJECT STARTS ON 1AUG92



"best" confirmation/test wells as part of their on-going water supply program.

Test Drilling and Equipment Procurement

The selection and procurement of materials will be conducted in a manner similar to that described for the work in Tigray province. If new rigs cannot be purchased, existing Halco V866 rigs will be used for the drilling in the Ogaden. Some spare parts and equipment to upgrade their conditions and capacity would be required. (See Appendix III).

Test drilling would be conducted with Ethiopian Government rigs, equipment and personnel used to construct UNICEF wells in the region. Well construction materials, spare parts and equipment will be procured in a manner similar to that described for the work in Tigray province.

Special Geophysical Field Investigations

Mr. Bisson's team recognizes the salt contamination problem (gypsum, etc., deposits) of the Ogaden which has plagued GOE drilling efforts. Special techniques and emphasis will be placed upon mapping and working those areas which possess low salinity groundwater.

The geologic situation (high salinity groundwater) created by the presence of gypsum beds within the sedimentary sequences of the Ogaden region requires special airborne geophysical investigations be undertaken to differentiate among regions containing low and high salinity water. Use would also be made of airborne survey data collected by oil and gas exploration companies previously or currently working in the Ogaden.

Once these special analyses are completed, well sites will be selected so as to optimize both water quantity and quality, avoiding highly saline groundwater which has been encountered in almost three quarters of the bedrock test wells drilled by others to-date in the Ogaden.

Project Activities and Schedule

Given the urgency of human need, Mr. Bisson's team plans to combine the exploration and test drilling components in a leap frog fashion so that test drilling immediately follows on-ground geophysical testing at each Priority Target Area (PTA) while geophysical testing continues at other sites. The project schedule for the Tigray and Ogaden regions is charted on the following pages as is the Phase/Task Flow Diagram for the Exploration/Testing program in Ethiopia. (A similar program will be implemented in Botswana).

BOTSWANA ACTION PLAN

In-Country Evaluation

Botswana possesses a stable economy and a progressive government, with abundant natural resources and a promising future, with one major constraint -- the unpredictable nature of its national water supply. Inadequate or underdeveloped resources lead to chronic shortages in critical urban areas and uncertainty about long-term sustainability for mining and other commercial applications.

These water problems, underscored by the current, acute regional drought, have resulted in government water delivery strategies employing a variety of already identified ground and surface water sources throughout the country. Several of these proposed water projects, involving hundreds of millions of US dollars in government expenditures are currently in the advanced planning process. They are targeted primarily on surface resources, but could pose some significant environmental, wildlife, and/or tribal/economic participation conflicts.

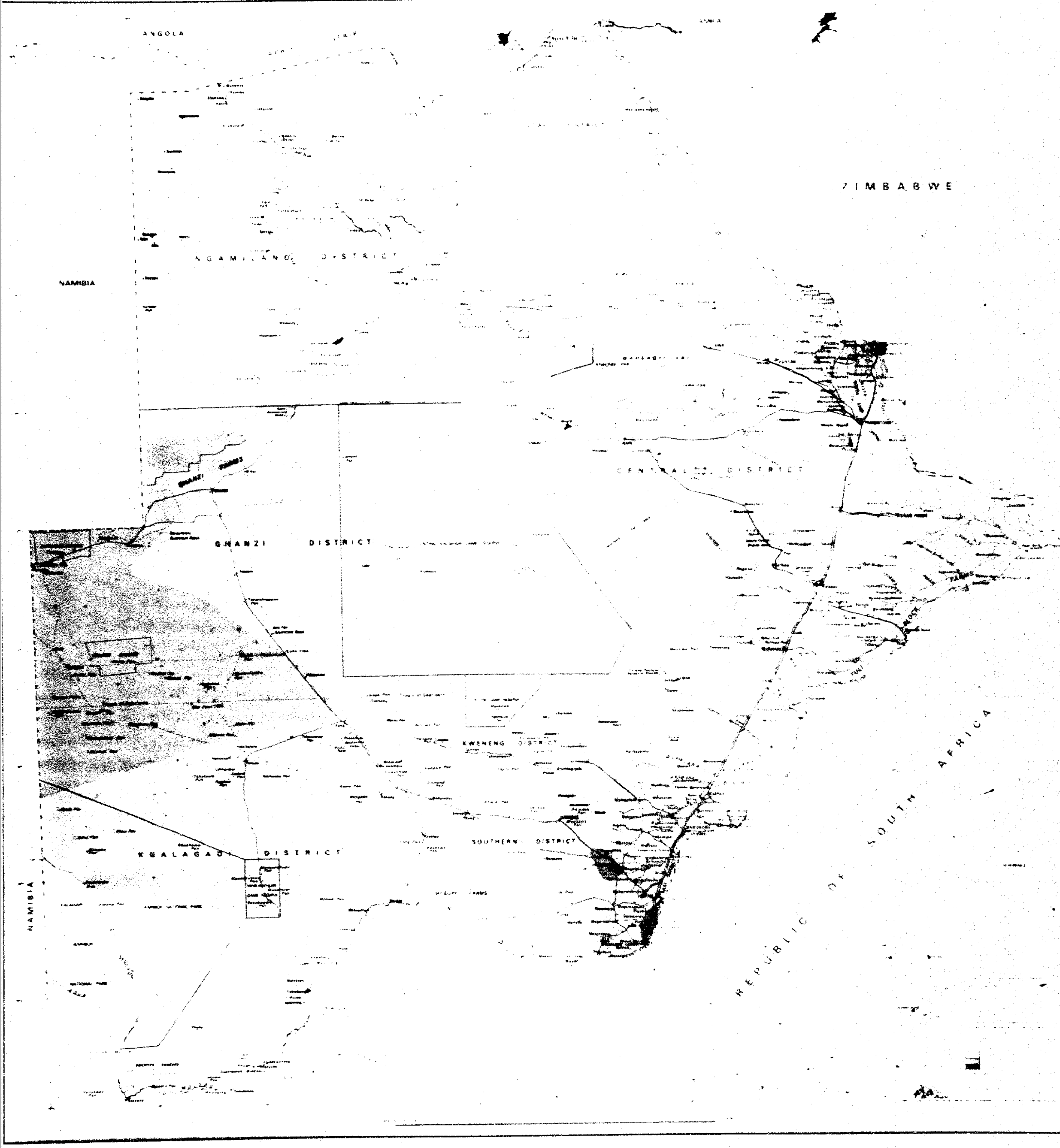
In 1991, Mr. Bisson proposed that USAID consider funding a two-phased pilot program to map Megawatersheds in Botswana and the surrounding region through identification of regional groundwater pathways in fractured rocks. This would provide critical information concerning the location and availability of groundwater resources associated with Rift-induced secondary permeability in the SADCC states. This information could be used by Government of Botswana (GOB) and SADCC planners to more economically address long-term water needs as well as immediate water shortages resulting from the ongoing severe drought.

Mr. Bisson would use a proprietary exploration technology, previously proven by his team in the Horn of Africa, to map and test the region's Megawatersheds. Mr. Bisson, who designed and implemented these prior projects for USAID, has also spent considerable time and effort in southern Africa in the 1980's examining hydrogeological data and had concluded at that time that Botswana possesses a poorly understood, but highly favorable groundwater environment in its fractured, consolidated bedrock.

A USAID/USGS evaluation of the proposed Megawatershed model (see Appendix I) as the basis for the pilot program in Botswana led to the USAID decision to contract with Mr. Bisson to perform the preliminary (Phase I) feasibility study. In Phase I, Mr. Bisson and his team were tasked with designing a results-oriented "action plan" to measure the potential for sustainable water development in a test region within Botswana. Such a pilot activity would demonstrate both the regional (SADCC)

THE REPUBLIC OF BOTSWANA

Scale 1:



nature of natural bedrock water storage and delivery systems, as well as substantial local benefits for Botswana, including dramatic increases in sustainable freshwater.

Botswana possesses a combination of natural and human circumstances which creates a highly favorable environment for optimizing the benefits derivable from careful development of a Megawatershed system, including

1. The ancient Africa Rift system has been actively fracturing the brittle rock underlying Botswana for hundreds of millions of years (see map - following page).

2. At the same time, fresh water has been physically and chemically (remember -- it is the universal solvent) forcing its way downward and outward through open bedrock fissures, while the Rift continued to create more and larger pathways for its flow.

3. It is probable that, for millennia, rainfall and the great rivers of southwest Africa have continued to feed vast quantities of new fresh water into these regionally permeable fracture systems.

4. Botswana has the greatest surviving and most prized surface manifestation of the Southern African Rift water system -- the Okavango River Delta -- as the blue/green ecological jewel of the Kalahari Desert (see LANDSAT mosaic - following). The economic value to the countries and cultural pride engendered by the Okavango in all Botswana were readily evident in every person encountered during our country visit. Everyone wants to maintain the integrity of the Okavango Delta, and the GOB has been singularly and consistently responsive to its citizens' preferences while grappling with the grim realities of its citizens' water needs.

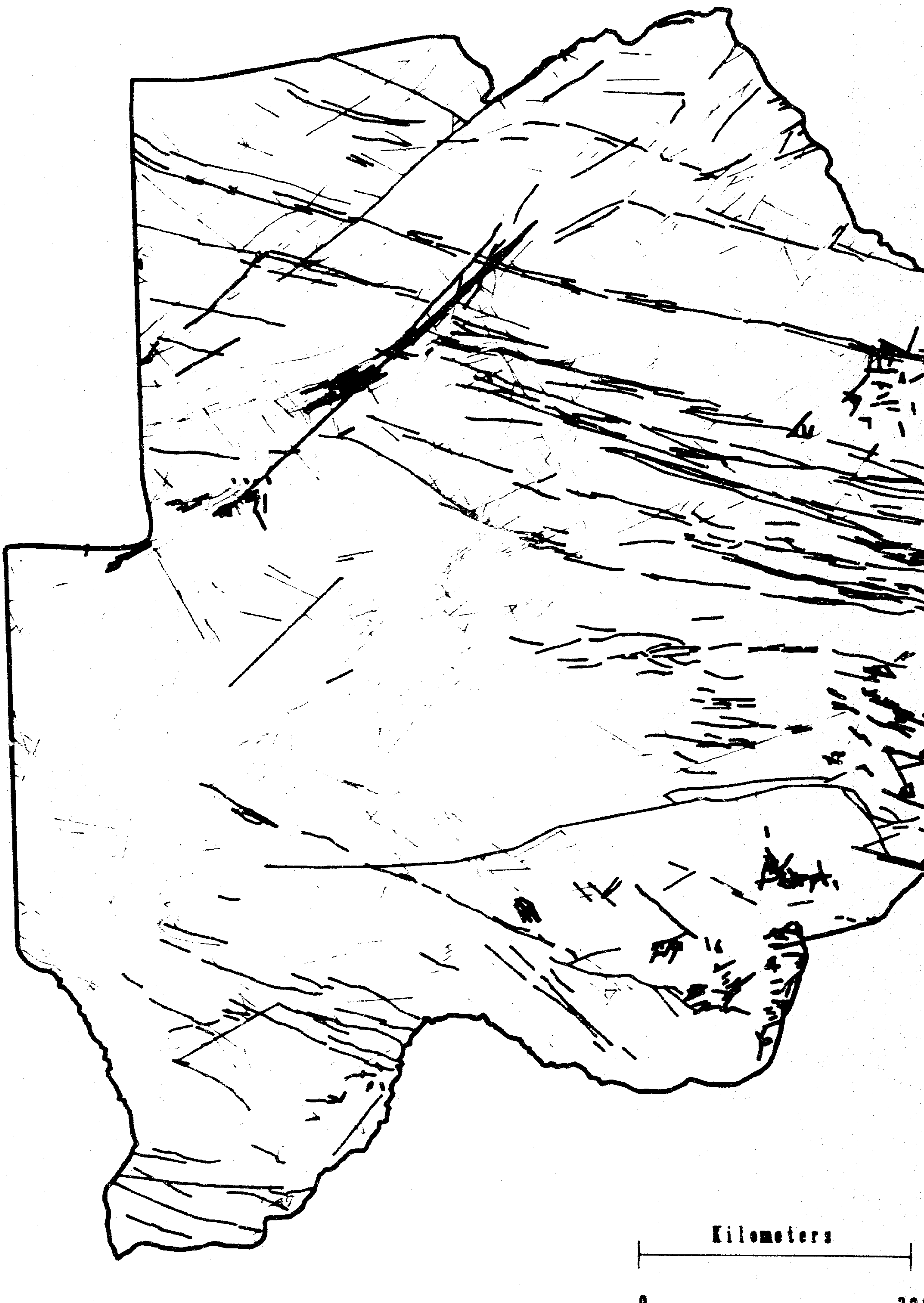
   In the face of critical water shortages from the current major drought and an absolute requirement to meet longer-term demands for domestic and commercial water, the GOB recently acted on advice from a team of international experts from the International Union for the Conservation of Nature (IUCN) about the viability of a major engineering proposal to use surface water from the Okavango Delta. The GOB cancelled this well-advanced project and decided to take a fresh look at all options. This difficult, but courageous GOB decision opens the way for alternatives never before seriously examined.

Okavango Region of Botswana

This mosaic of Landsat image-scenes illustrates the Rift-Fault controlled nature of most of the major surface water resources in Southern Africa. Note that the Okavango Delta in center image is surrounded by and permeated with these huge fault/fracture systems.

Some hydrologists ask the question: "with all that water running over all that fractured rock, can gravity be ignored?" The Makgadikgadi Pans shown to the east of the Delta (in blue and white) may be the ultimate destination and evaporation pan for regional groundwater flows originating in the Okavango, Chobe and Zambezi river systems.

This colorful photo-image and the many questions it evokes was part of an exhibition at the Earth Summit in Rio de Janeiro where participants gained new insights on groundwater in Africa.


Kilometers

FAULT LINES

REPUBLIC OF BOTSWANA

Lineament, observable on bedrock kalahaki beds in satellite imagery

Dolerite dykes and dyke swarm (potentially faulted)

Fault

Inferred Fault

Fault in pre-karoo sequence geophysically indicated

This map series is part of the Botswana and Ethiopia Megawatersheds pre-feasibility study written by Robert A. Bisson. The study goals include the demonstration to USAID, the governments of Botswana and Ethiopia, other african countries and international aid and development institutions of the critical nature of regional and national water resource management strategies in drought relief disaster mitigation and development planning. These strategies can be efficiently designed and implemented using a Geographic Information System (GIS).

Geographic Information Systems (GIS) is an information technology which stores, analyses, and displays both spatial and non-spatial data. It is a decision support system involving the integration of data in a problem-solving environment. This map represents one of the ways of displaying spatial and attribute data.

The Lambert Conformal projection was used for this map. Standard parallels are 18 00 00 & 26 00 00 S and the central meridian is 25 00 00 E.

This map was produced for GIS demonstration purposes from Botswana Geological Survey Department map 1984. GIS analysis provided by PADCO under contract with Robert A. Bisson.

PADCO

June, 1992

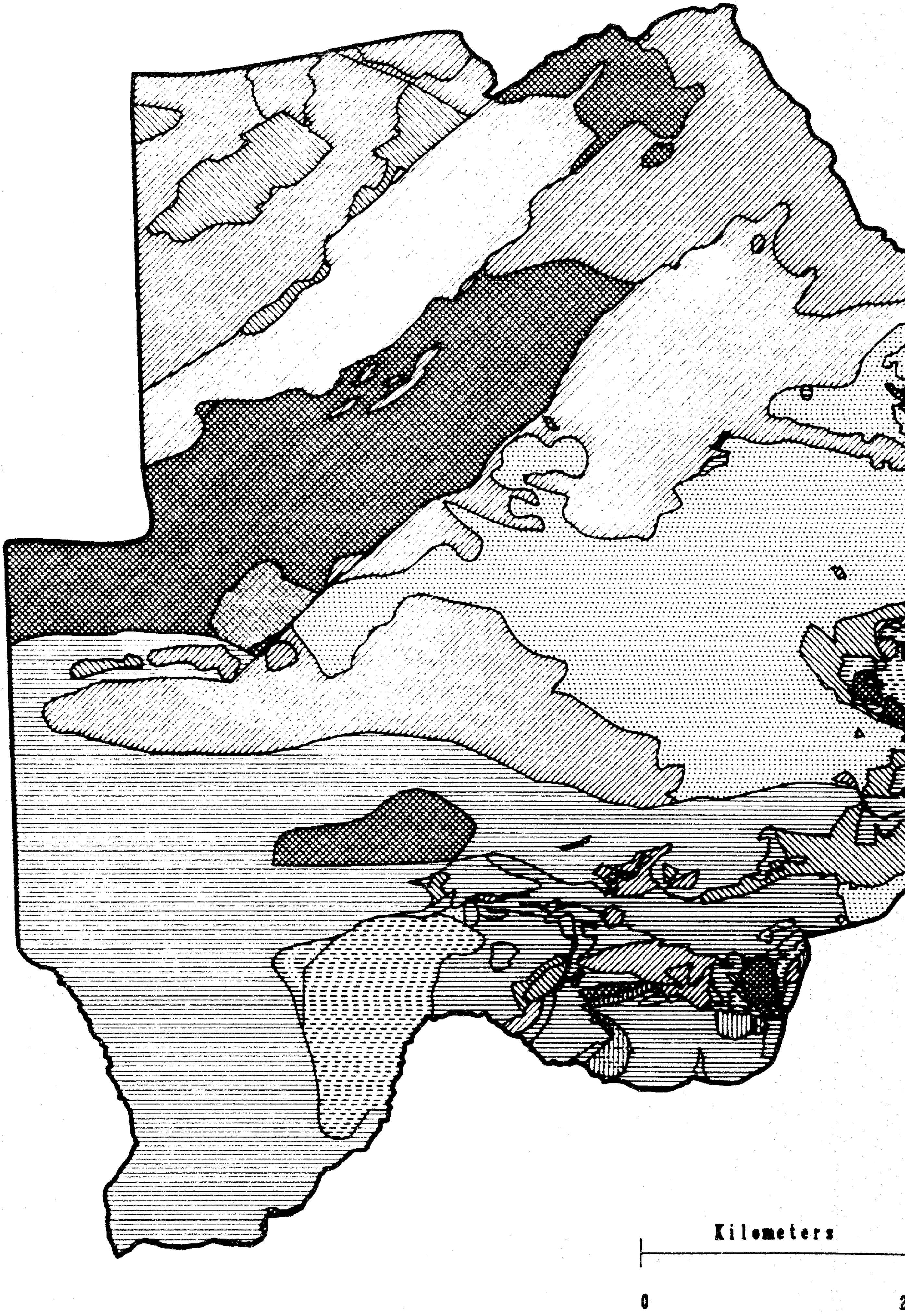
Mr. Bisson's Botswana field work and discussions underscored the stark contrast between the long-range vision of the political leadership governing Botswana and other countries facing similar deficiencies. The GOB, with assistance from in-country expert and others, including specialists from the IUCN, has deliberately and intensively refocused its efforts to discover the nature and extent of <u>all</u> of Botswana's water resources. This creates an opportune environment for including the Megawatershed Model as an element of the GOB's comprehensive resource assessment.

5. The technical sophistication of the engineers and geohydrologists of the Department of Water Affairs (DWA) within the Ministry of Mineral Resources and Water Affairs, is of a high calibre, creating a compatible, team-building capability for follow-through in Megawatershed strategic water development planning, based on a disciplined program of testing and monitoring across the country. The DWA also possesses an operating GIS and is directed by Mr. Sekwale, a highly-qualified and experienced geohydrologist whose interest in the nature and extent of secondary (fracture) permeability in Botswana was manifest throughout an extensive interview.

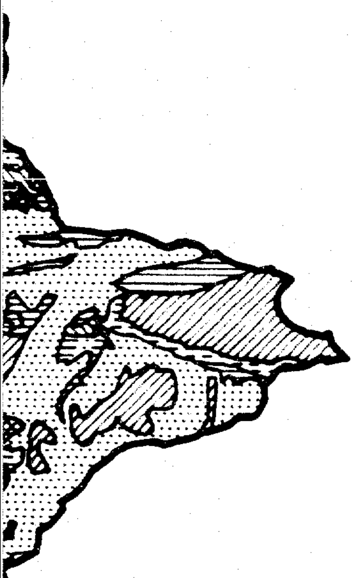
6. The DWA possesses drilling equipment and technology which, with modest modifications and augmentation, should successfully penetrate even the fractured hard-rock environments of Eastern Botswana, intersecting high-yield aquifers and permitting accurate testing of aquifer potential.

7. The Botswana Geological Survey and the DWA have amassed a considerable amount of mapped data and carefully archived publications. In addition, other recent published and unpublished data and reports were examined during this prefeasibility study. A review of all materials clearly indicates little need for major new reconnaissance level or general surveys. Rather, a simple change in perspective in evaluating existing information will have a dramatic effect on future results of groundwater investigations.

8. In Phase II, the first test site in Botswana would be identified in less time than in Ethiopia because of the excellent communications links, transportation (see map - following pages), existing in-country technology, the expertise of the GOB water professionals, and other favorable factors. At the same time, while addressing drought priorities,



Kilometers
0



GEOLOGY

REPUBLIC OF BOTSWANA

- Amphibolite after metamorphism
- Dolerite sills ages registered ca.
- Felsite kanye volcanic formation
- Tonalite
- Migmatitic gneiss
- Granite, adamellite, tonalite, anatectite
- Monzonite, tonalite, granite
- Feldspathic sandstone, shale
- Banded ironstone
- Arkose, carbonaceous mudstone, coal
- Porphyritic felsic lava
- Orange, red or white aeolian sandstone
- Basalt
- Norite, gabbro
- Schist, quartzite
- Purple to white orthoquartzite
- Dolomitic limestone
- Siltstone flags
- Red sandstone
- Shale, siltstone, limestone
- Conglomerate, course to fine sandstone
- Marble
- Synite, diorite
- Dolomite, chert, shale, quartzite
- Banded ironstone
- shale, sandstone
- Quartz
- Gneissic rocks
- Gneissic rocks within the Damara oregen
- Diorite, pyrroxenite
- Greywacke, felsic porphyry

This map series is part of the Botswana and Ethiopia Megawatersheds pre-feasibility study written by Robert A. Bisson. The study goals include the demonstration to USAID, the governments of Botswana and Ethiopia, other african countries and international aid and development institutions of the critical nature of regional and national water resource management strategies in drought relief disaster mitigation and development planning. These strategies can be efficiently designed and implemented using a Geographic Information System (GIS).

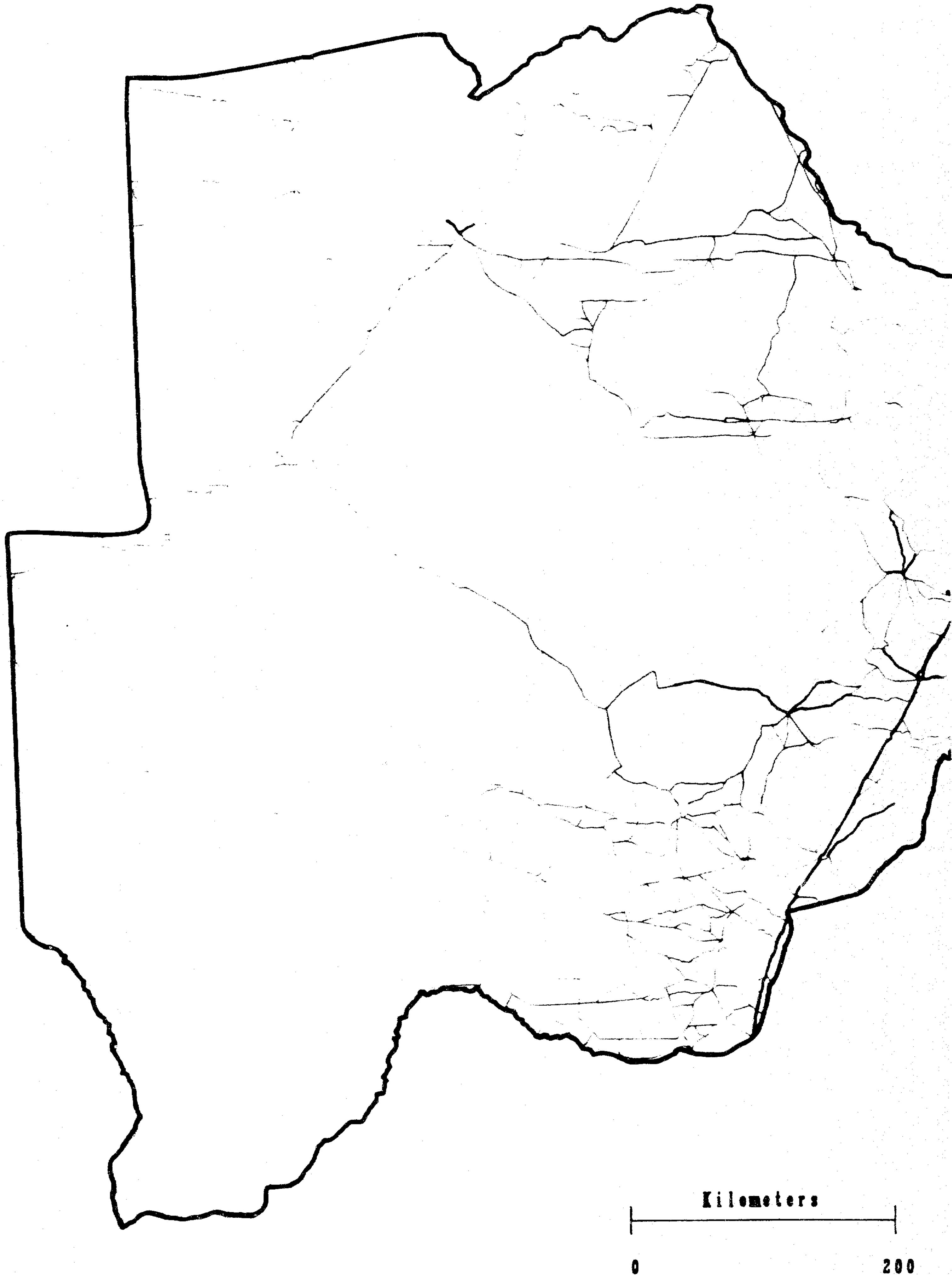
Geographic Information Systems (GIS) is an information technology which stores, analyses, and displays both spatial and non-spatial data. It is a decision support system involving the integration of data in a problem-solving environment. This map represents one of the ways of displaying spatial and attribute data.

The Lambert Conformal projection was used for this map. Standard parallels are 18 00 00 & 26 00 00 S and the central meridian is 25 00 00 E.

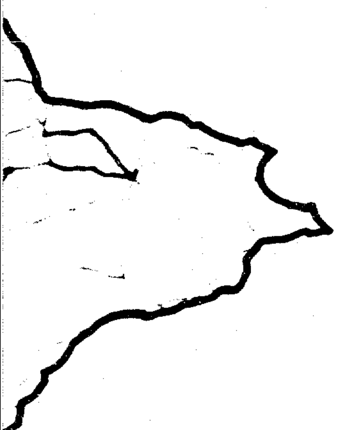
This map was produced for GIS demonstration purposes from Botswana Geological Survey Department map 1984. GIS analysis provided by PADCO under contract with Robert A. Bisson.

PADCO

June, 1992 V.Z.



Kilometers
0
200



ROADS AND RAILROADS
REPUBLIC OF BOTSWANA

Primary or secondary roads or highways

Tracks, trails or footpaths

Connector

Railroads

This map series is part of the Botswana and Ethiopia Megawatersheds pre-feasibility study written by Robert A. Bisson. The study goals include the demonstration to USAID, the governments of Botswana and Ethiopia, other african countries and international aid and development institutions of the critical nature of regional and national water resource management strategies in drought relief disaster mitigation and development planning. These strategies can be efficiently designed and implemented using a Geographic Information System (GIS).

Geographic Information Systems (GIS) is an information technology which stores, analyses, and displays both spatial and non-spatial data. It is a decision support system involving the integration of data in a problem-solving environment. This map represents one of the ways of displaying spatial and attribute data.

The Lambert Conformal projection was used for this map. Standard parallels are 18 00 00 & 26 00 00 S and the central meridian is 25 00 00 E.

This map was produced for GIS demonstration purposes from digitized base maps. GIS analysis provided by PADCO under contract with Robert A. Bisson.

PADCO

June, 1992 V.Z.

the opportunity also exists to carry out a broader mapping and testing project, with all facets of potential future water development evaluated "in matrix" with other criteria using the Botswana GIS. **In other words, a model planning process could be developed in Botswana which would become Africa's most "user-friendly" and therefore practical solution, where water availability is the limiting variable.**

Study Region: Eastern Botswana

Prior to his recent country visit, Mr. Bisson's geographic focus was in the central and northwest region of Botswana. However, based on interviews with GOB officials, Mr. Bisson is recommending to USAID that the more populated, eastern region of Botswana be considered as a priority target area for the pilot program. This eastern region also possesses the potential for Rift-related geologic structures that create the favorable groundwater environments known as Megawatersheds. This region also has a bedrock terrain with which Mr. Bisson's team is very familiar. The target area is the most drought-affected region of Botswana. With surface waters at minimal levels (see photos at front of report -- Victoria Falls), the pilot project would provide the opportunity to immediately access sustainable regional groundwater sources.

To reasonably begin to evaluate the nature and extent of the regional Megawatersheds of Botswana, the proposed pilot program could be completed within twelve months, with first test wells drilled within three to four months.

A crucial part of the success of a pilot project of this nature will be the active support of the GOB in the strategic planning for, and implementation of the project, including data sharing, field activities, test drilling, pump testing and water quality analysis. GOB officials have indicated their interest in the proposal. The results of the pilot mapping/testing program will be documented on a GIS in a format which is directly transferrable to the GOB's existing databases, for use by resident Department of Water Affairs experts.

Based upon the pilot program's success and availability of support, this concept could be expanded elsewhere in Botswana to help the government with its water development and management program.

Project Activities and Schedule

The flow charts on the following pages describe the exploration, drilling and testing/reporting process flow which would be carried out in a results-oriented fashion, in concert with the previously-described Ethiopian projects.

Mobilization to perform water exploration can be accomplished within fifteen days of execution of a contract.

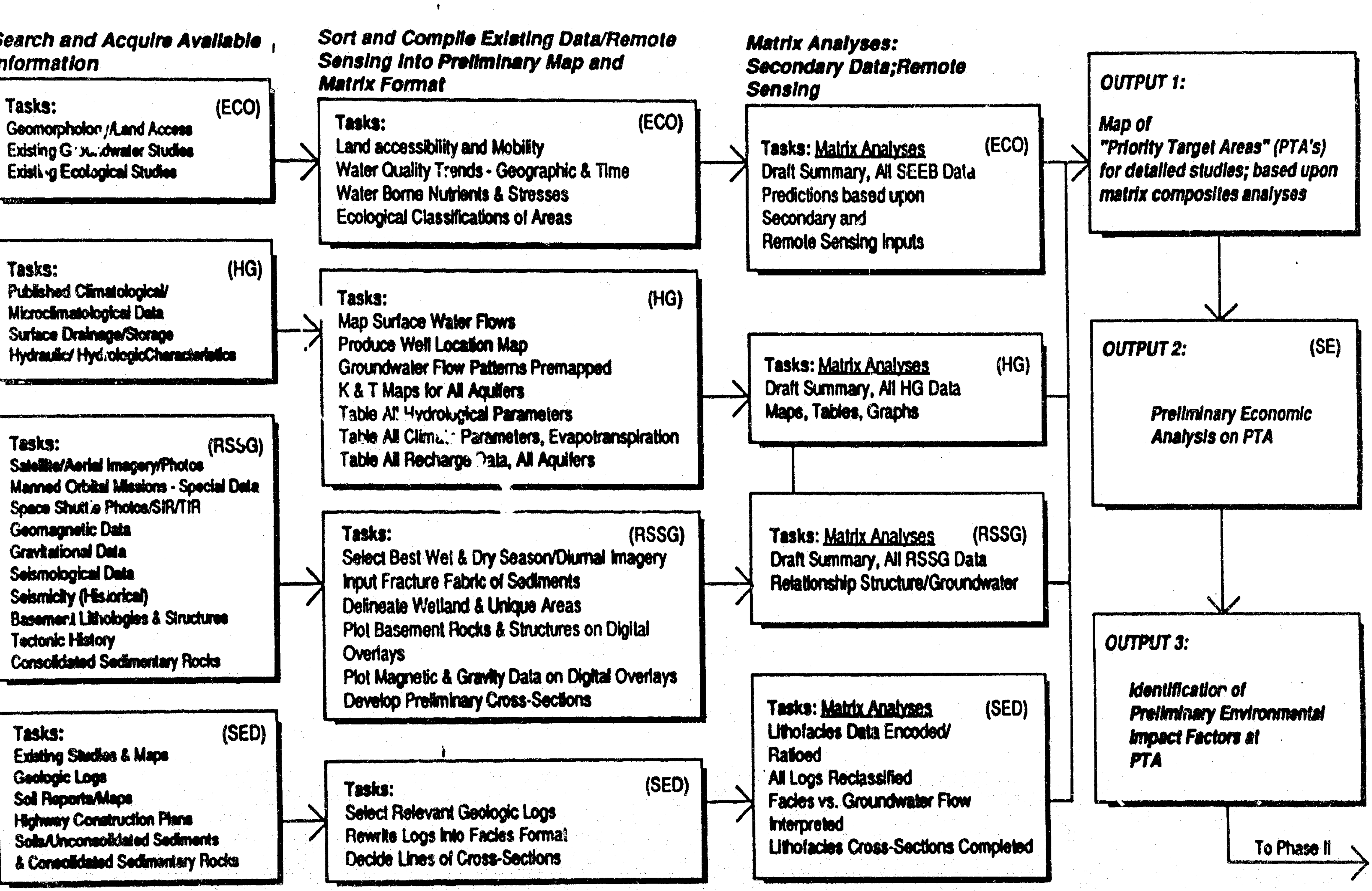
Mr. Bisson and his team would perform immediate follow-up work in-country to secure commitments for manpower, rigs and equipment, obtain technical data existing only in Southern Africa, arrange for in-country transportation and fuel, procure shipping/customs clearances for equipment and continue liaison with government and relief agencies.

Test drilling at the First Priority Target Areas can begin within ninety to one hundred and twenty days of contract commitment. The ensuing drilling and testing program is designed to run for three to six months and to overlap with the mapping program.

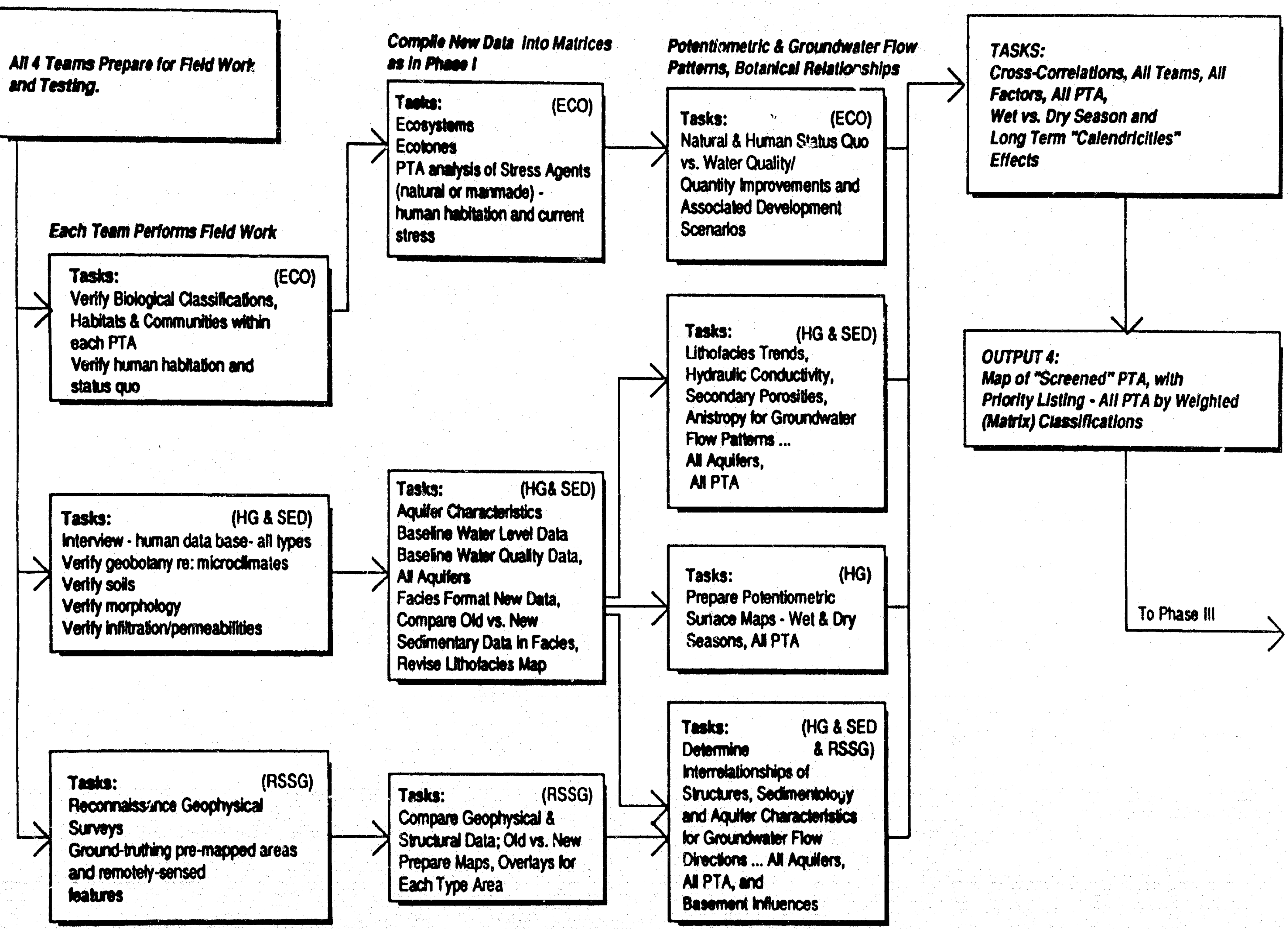
The strategic water map would become a "working tool" within two months (with initial test drilling sites identified) and could be completed within six to seven months of project commencement. Ongoing exploration efforts and the refinement of the water resources map can then be accomplished by Mr. Bisson's team and in-country personnel trained for the project.

Once the exploration model has been verified in Eastern Botswana the team could assist local officials, USAID, and other agencies in developing a program for expanding the water exploration and special drilling technology to the rest of Botswana.

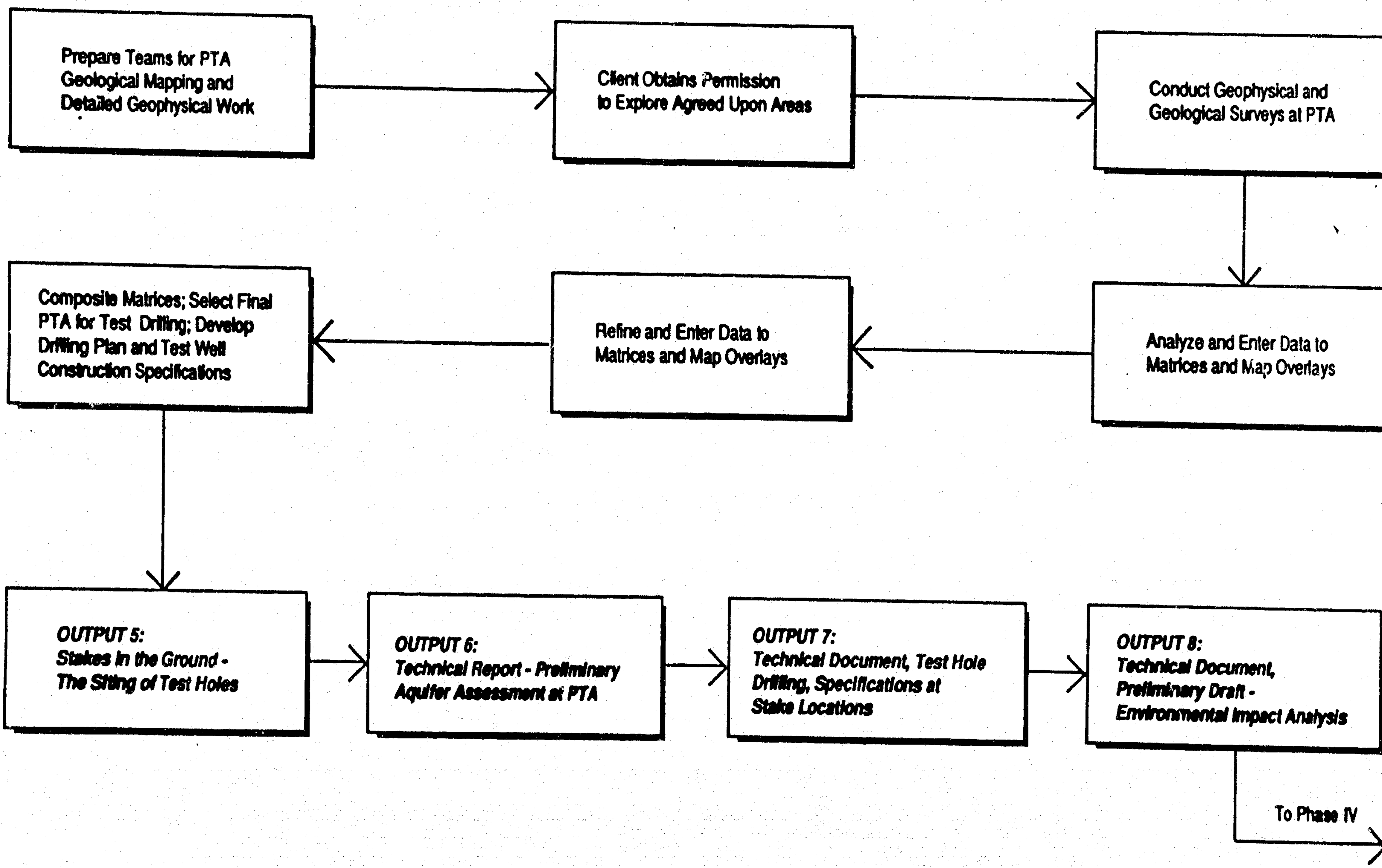
PHASE I - DATA ACQUISITION, COMPILATION, REVIEW, SYNTHESIS, AND INTERPRETATION OF ALL AVAILABLE INFORMATION



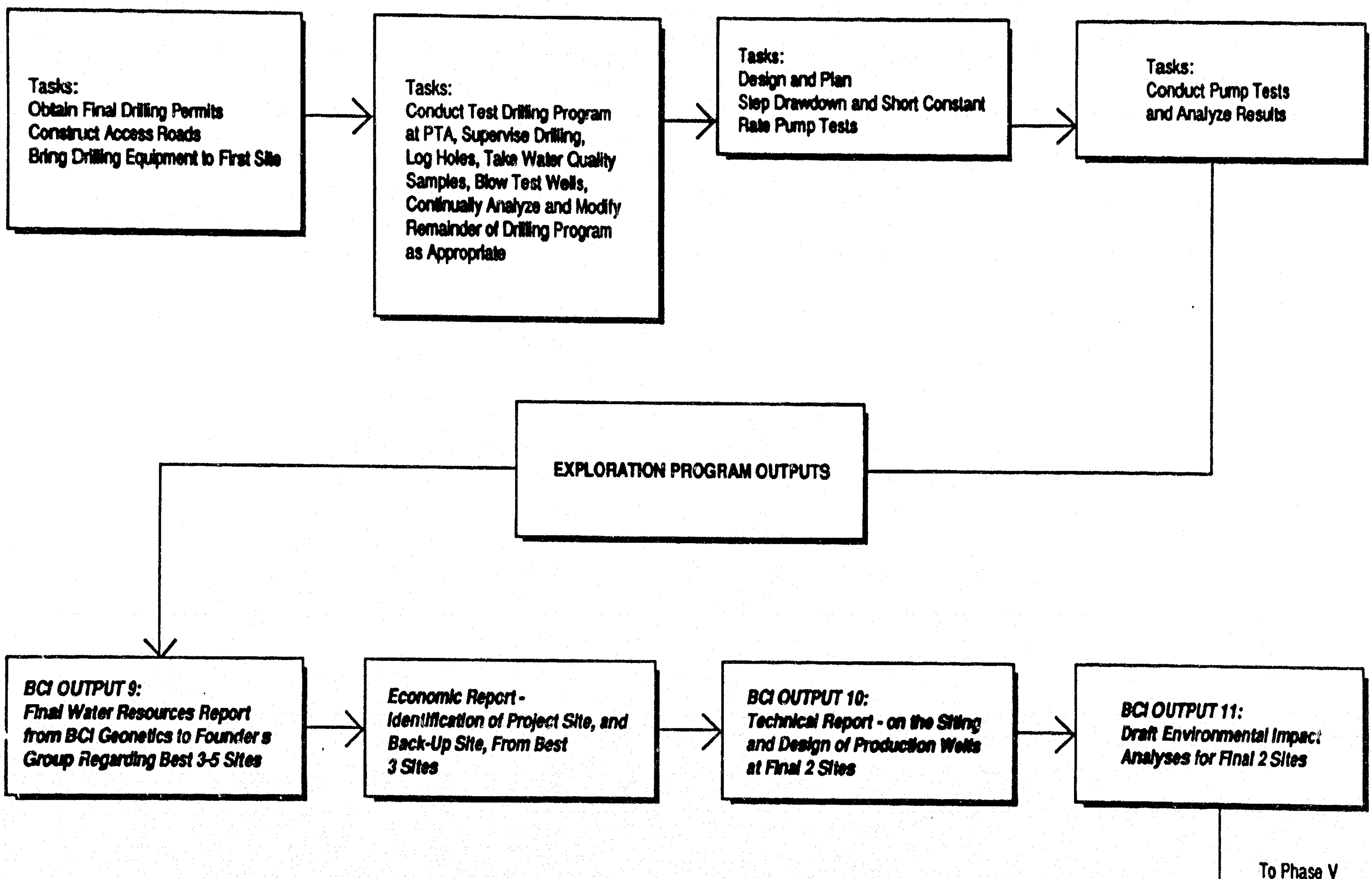
PHASE II - FIELD RECONNAISSANCE OF DESIGNATED "PRIORITY TARGET AREAS" (PTA)



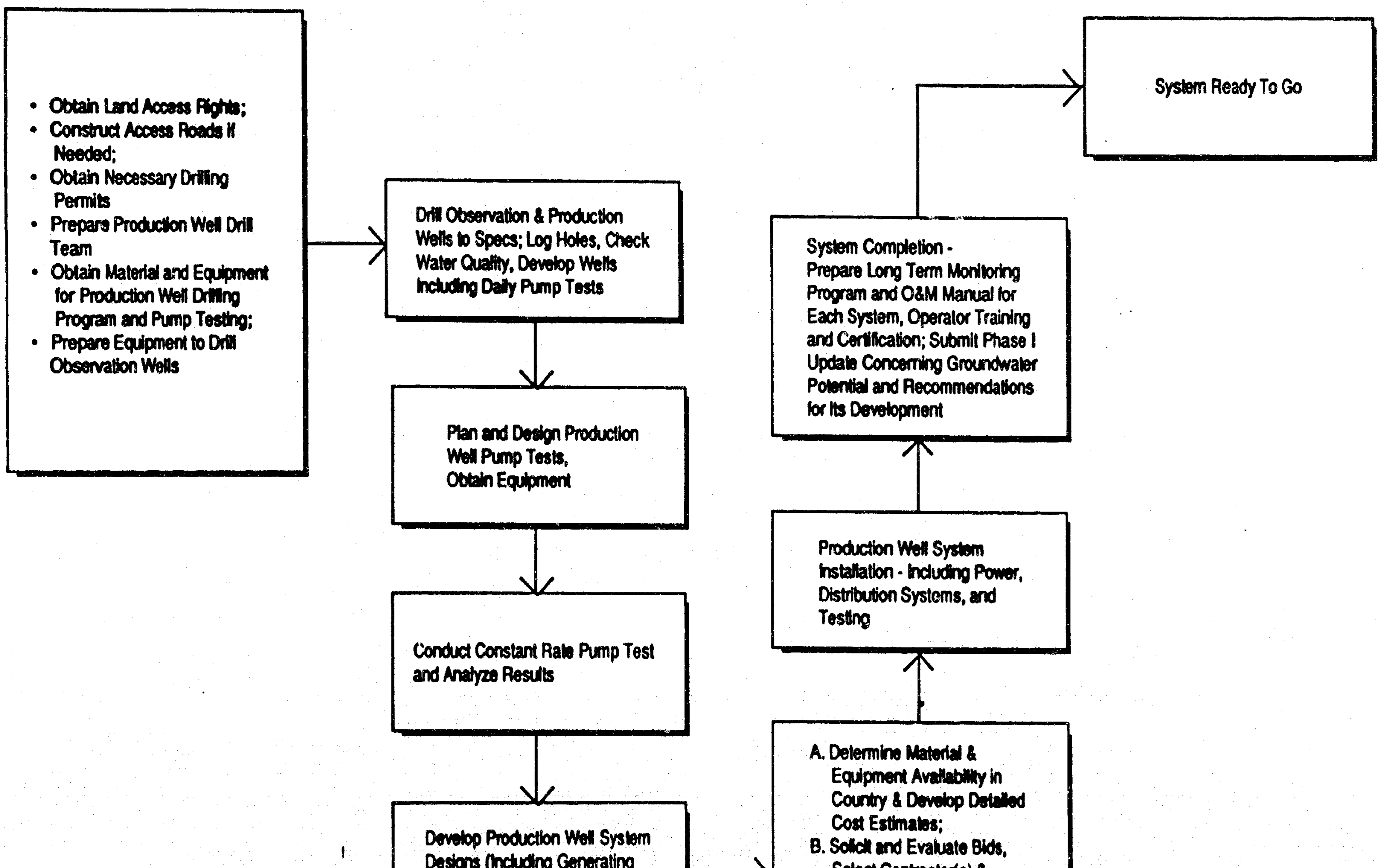
PHASE III - HIGH-RESOLUTION MAPPING - LOCATING OF TEST WELLS



PHASE IV - TEST HOLE DRILLING AND PUMPING TESTS

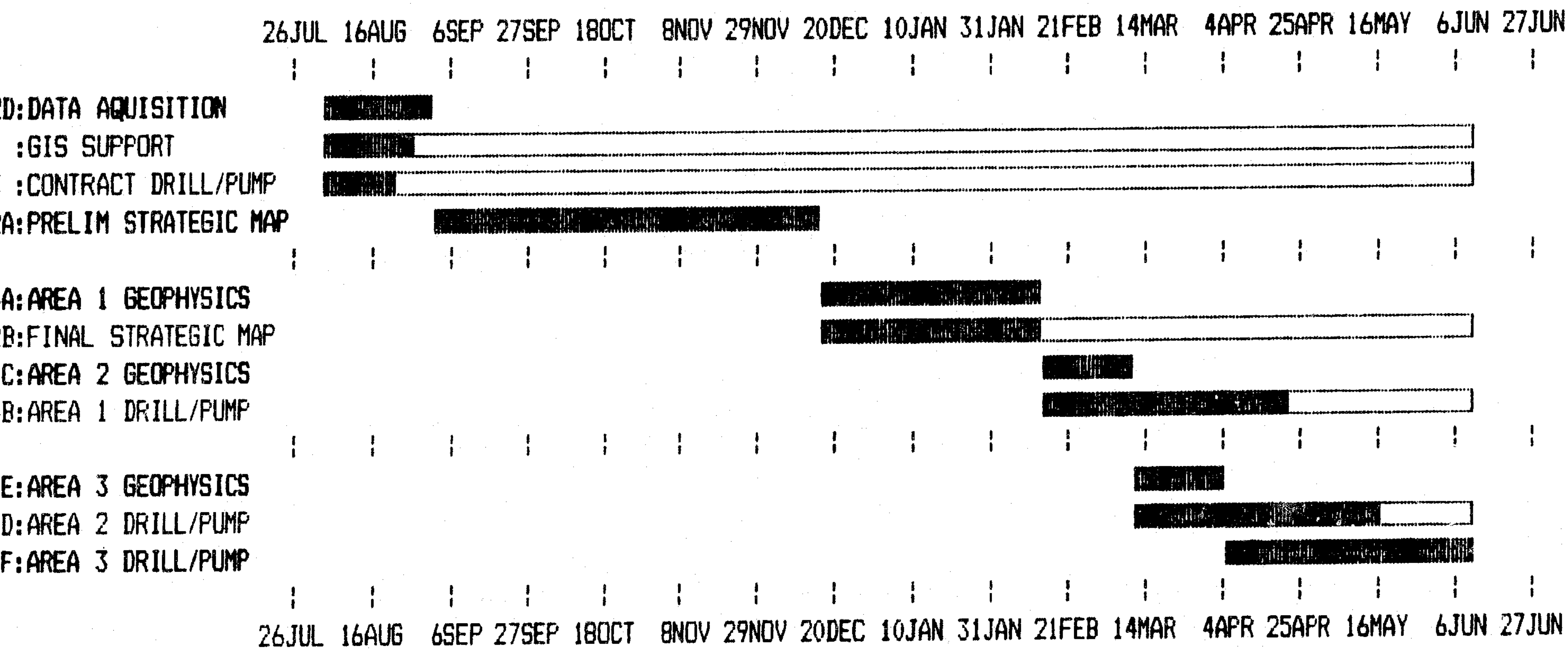


(FUTURE) PHASE V - PILOT DEVELOPMENT PROJECT: PRODUCTION WELL SYSTEM INSTALLATION



EASTERN BOTSWANA

1:11 ON 06/25/92 PROJECT STARTS ON 1AUG92 PAGE 1



PHASE II BUDGET

The Phase II budget will be designed to support an integrated, results-oriented project involving the simultaneous mapping, drilling and pump testing of three regions in Africa.

To achieve near-term objectives with optimum efficiency, Mr. Bisson proposes that the Phase II program be carried out using his field proven team and methods.

The exploration program is designed to find water and make it available to the people who need it as soon as possible, while continuing the Megawatershed "proofing" and strategic mapping process. Mr. Bisson's team would carry out the exploration mapping, test well siting, test well design, drilling equipment specifications, supervision of drilling operations and test pumping, as well as technical evaluation of water quality and sustainable yields. The host countries would provide basic drilling rigs. Botswana has resources to "tool up" its own rigs to Mr. Bisson's specifications while Ethiopia's Government drilling equipment must be upgraded (see Appendix III) by donors (UNICEF, AID, etc.). Further, host country personnel, along with UN agency specialists, would be responsible for inputting priority siting criteria to the team's base maps and for making final decisions on drilling site preference (among the favorable water options presented by Mr. Bisson's team). These in-country experts would also be responsible for water allocations to refugees, etc., during and after test pumping of the test wells.

The Phase II budget is in preparation and will be discussed and submitted to USAID at the appropriate time. The table on the following page describes the basic budget criteria.

Part I -- USAID Contributions

Objective 1a	Strategic Map	
	Ogaden	$
	Tigray	$
	Botswana	$
Objective 1b	Test Well Siting, etc.	
	Ogaden	$
	Tigray	$
	Botswana	$
Objective 2	Contract of In-country Drilling and Test Pumping Equip.	
	Ogaden	$
	Tigray	$
	Botswana	$
Objective 3	Test Well Drilling and Pumping	
	Ogaden	$
	Tigray	$
	Botswana	$

Part II In-Country/Donor Contributions

Ogaden	$
Tigray	$
Botswana	$

PHASE II TEAM

Overview

Mr. Bisson's proposed Phase II exploration and management team is principally comprised of professionals with whom he has worked closely in Africa and the US for many years. The Phase II Pilot Program would be performed as a fixed price contract (or contracts) with Mr. Bisson, who would have overall responsibility for the project. As he did with the Phase I prefeasibility contract, Mr. Bisson would subcontract technical and administrative work to appropriate professionals, who are principals in other independent firms. The team is assembled, has participated in aspects of the Phase I project design work and field investigations, and is prepared for immediate Phase II project implementation.

Technical rationale for sole source contracting and team qualifications for this project were evaluated by USAID experts in advance of prefeasibility contract execution. Confidential details concerning the identity and qualifications, as well as services of team members will be contained in a separate, proprietary cost proposal which will be presented to the USAID Contracts Officer during negotiations.

Mr. Bisson's role in this geographically dispersed, but highly integrated exploration program, is to use his unique experience in running such programs in Africa. He will apply proprietary technology to design, direct and coordinate the exploration programs in Ethiopia and Botswana and incorporate the technical outputs from his team's field and laboratory work into maps and reports which identify the best well sites within the newly charted Megawatersheds. These sites will represent the most favorable combination of natural characteristics and human need to both calibrate the Megawatershed models and provide fresh water for refugees and other drought stricken people in Ethiopia and Botswana.

Mr. Bisson will also provide overall project management, and liaison/communication with key USAID and host country officials. As previously discussed, it is also important to work toward a "paradigm shift" in water development planning at other institutions, such as the OECD, World Bank, , UN agencies, etc. Mr. Bisson will assure opening of and continued communications with these other institutions.

In Ethiopia, based on prior successful water mapping by Mr. Bisson for United States Agency for International Development (USAID) in the Horn of Africa and the use of the same proprietary approach in solving refugee water problems, USAID agreed that Mr. Bisson should carry out a preliminary feasibility study. To assess the practical, near-term potential to improve water access for refugees and people in otherwise economically viable sections of the Ogaden and Eritrea (or other) regions and design a pilot water mapping/testing program (Phase II) to deal with the problem. An expanded understanding of water resources and the application of advanced well-siting and drilling techniques would increase the cost-effectiveness of refugee assistance and disaster mitigation programs.

Based upon prior investigations of the area by Mr. Bisson's team and new information gained during interviews with Ethiopian government officials and other experts inside Ethiopia and in the US, the Phase I team was able to answer several questions of feasibility, including promising target regions, time frames and costs for Phase II mapping and test drilling, test pumping, and the possibility for employing Geographic Information System (GIS) techniques to enhance local or national resource development planning.

In Botswana, a USAID review of Mr. Bisson's technical rationale for a Megawatershed underlying the Zambezi/Okavango region and the possibility that natural bedrock water storage and delivery systems may exist in other Southern African Development Coordination Conference (SADCC) states, resulted in a contract with Mr. Bisson for a preliminary feasibility study. The study goals, which have been met, included a survey of the Government of Botswana's water needs and interest in exploring alternatives, water development technologies and a pilot/test program, an evaluation of the practicality of the Megawatersheds concept, and the possible location and cost of a demonstration pilot program (Phase II, conceptual mapping and test drilling).

Mr. Bisson's overall conclusion in both countries is that the application of this refined US water exploration technology, and special mapping and drilling techniques, promise to be cost-effective alternatives to current water resource development. The recommended Phase II exploration and mapping activities can identify the best available sites for sustainable yields of high quality water from expertly drilled wells. In Ethiopia, the drilling of test wells would also hopefully result in high quality water supplies in proximity to refugee camps or populations most affected by the drought conditions.

The Phase II demonstration activities should also help calibrate the Megawatershed Model at both ends of the Africa Rift System, further expanding knowledge about the phenomenon and exploration concept.

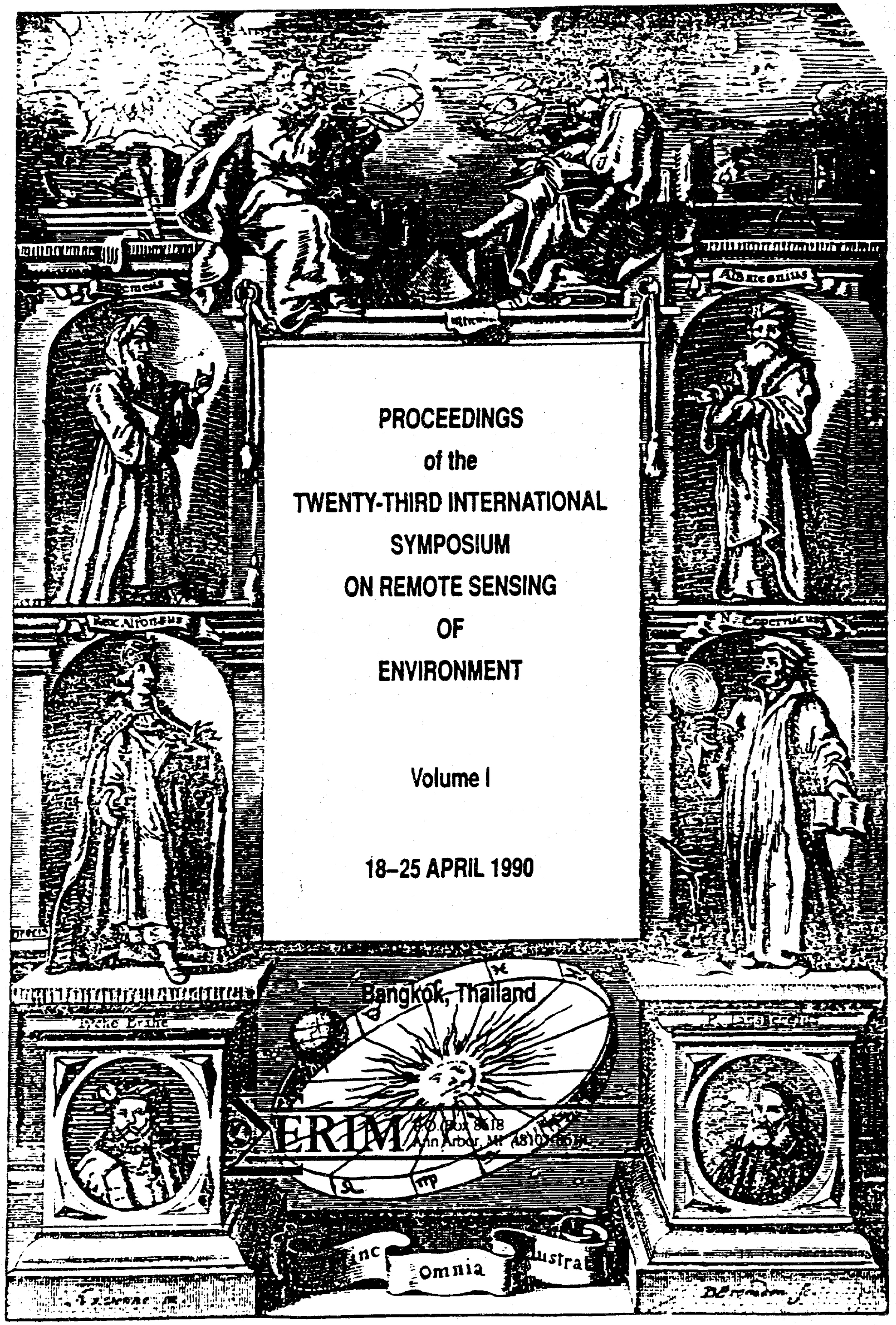
APPENDIX I
Megawatershed Model

PROCEEDINGS
of the
TWENTY-THIRD INTERNATIONAL SYMPOSIUM ON REMOTE SENSING OF ENVIRONMENT

Volume I

18–25 APRIL 1990

Bangkok, Thailand



MEGAWATERSHEDS EXPLORATION MODEL

Robert A. Bisson
BCI Geonetics, Inc.
Laconia, NH 03247 USA

and

Farouk El-Baz
Boston University
Boston, MA 02215 USA

ABSTRACT

The megawatershed model is a concept of the behavior of groundwater in large-area watersheds. It is designed to enhance success in the exploration for groundwater, particularly in fault-controlled regions. In such regions surface and subsurface water flow may be strongly influenced by structural features. The latter constitutes zones of secondary permeability through which large amounts of water may flow.

Recognition of the significance of such a model was largely due to the availability of space photographs, which cover large areas of the Earth and allow the interpretation of regional patterns, and the correlation of drainage with structure.

The model takes into account the water source from precipitation, the catchment area, the infiltration process, the transmission mechanisms, and the water storage capacity of the system. An example of the application of the model to groundwater exploration is given in the Red Sea Province of eastern Sudan.

INTRODUCTION

The Megawatersheds Exploration Model was developed by the authors as a tool to enhance success in groundwater exploration. It is an exploration model rather than a quantitative hydrogeologic model.

*Presented at the Twenty-Third International Symposium on Remote Sensing of Environment, Bangkok, Thailand, April 18-25, 1990.

The term megawatershed in this context describes the broadest possible three dimensional catchment area and transmitter of water, originating from one or more recharge zones, and with surface and subsurface flow strongly controlled by regional structural features in the bedrock. Some of these structural features act as zones of secondary permeability, through which large amounts of water may flow (Figure 1). In this case, mega refers more to order-of-magnitude effects on groundwater flow in these three-dimensional fracture controlled systems than to areal basin size.

The purpose of the model is to better define these order-of-magnitude effects to assist in the discovery of large amounts of high quality groundwater, here termed "*high-grade water*" located within zones of secondary permeability. The "high-grade water" is attained when the measured yield from a well is an order of magnitude greater or more than the average yield of other wells in the region.

BACKGROUND

Large regional aquifer systems occur in many parts of the world. In many cases, the subsurface movement of water over long distances is a necessary ingredient of conceptual models of the dynamics of such aquifers. Most of the known regional systems, such as The Great Artesian Basin of Australia, the chalk aquifers of France and England, the Nubian Sandstone systems of North Africa and the Ogallala Formation of the High Plans Region of the USA are generally believed to occur entirely within sedimentary rock formations.

Also generally accepted is the view that aquifers in these sedimentary rock formations derive their characteristics from the imposition of climatic and hydrometeorological conditions upon the regional geology. With the exception of certain limestone terrains, primary properties of rock permeability and the geometry of associated sedimentary formations were in the past seen to represent the only major parameters affecting the occurrence of groundwater in sedimentary basins.

The premise of the megawatershed model is that, in addition to large watersheds underlain by sedimentary rocks, where primary porosity is assumed to control groundwater movement, there are also regional basins consisting of interconnected fracture systems. These can occur within watersheds underlain by both crystalline and sedimentary rocks.

Formal studies of groundwater behavior related to bedrock fractures have been carried out for more than a century. As early as 1835, William Hopkins, in *Researches in Physical Geology* listed his observation of rectangular arrangements in topographic features, drainage patterns, faults, mineralized veins, joints and alignment of springs. Dana (1847) contended that controlled re-establishment of the regional fracture system takes place along pre-existing patterned stress field lines; later confirmed by Cloos (1948) and Meinesz (1947). Hobbs (1911) stated that the development of land forms, in some areas, is largely the result of systematic bedrock fracture control and that these fracture systems propagate and manifest themselves on the earth's surface in the form of drainage alignments, linear topographic trends, soil-tonal anomalies and vegetation alignments; later confirmed by Hilgenberg (1949), Hill (1956), Henderson (1960 and Badgely (1965).

Historically, the propagation force has been attributed to earth tides, isostatic rebound, active crustal stress patterns, ocean floor spreading and differential compaction over an irregular basement. L. Casagrande (Mollard, 1957) indicated that a greater hydraulic gradient exists in the overburden

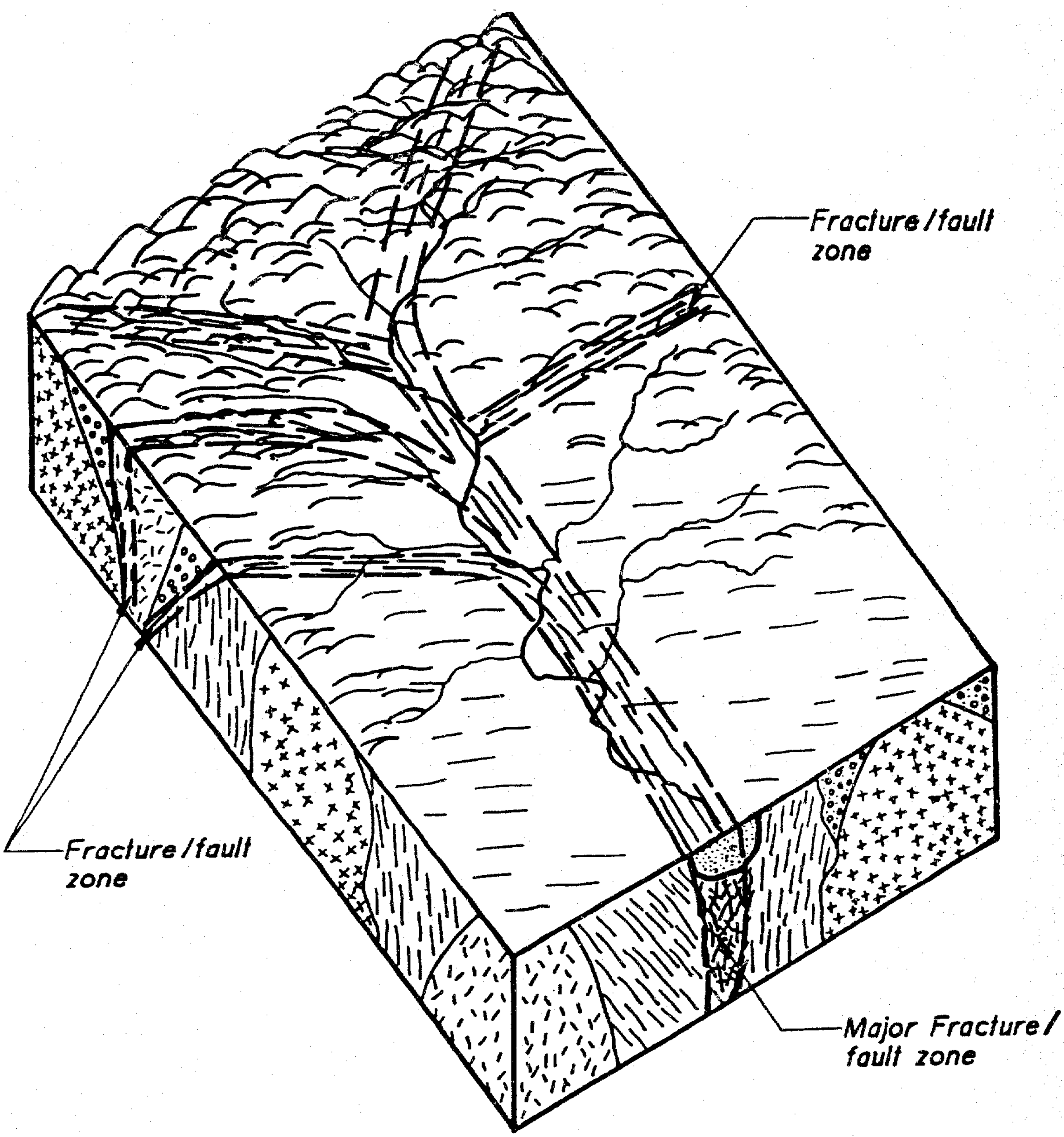


FIGURE 1: Schematic Illustration of the Control of Drainage by Major Fault/Fracture Zone.

above a fractured zone of bedrock. Downward movement of groundwater will cause a leaching of fine-grained particles and consequent subsidence. The fractured zone, under certain conditions, may act as a vertical conduit for discharging groundwater, accounting for higher soil moisture and corresponding vegetation alignments. Angelillo (1959) in his regional analysis of the Mohave River basin groundwater regime graphically described a stress-field induced and fractured-rock-controlled basin recharge and discharge system.

The advent of modern earth orbital platforms with remote-sensing instrument payloads, in the 1970's, combined with a concurrent wide acceptance of applied plate-tectonic theory, encouraged a new generation of explorationists to re-examine existing concepts in a new light.

In recent studies of aquifer systems, for example, Buckley and Zeil's (1984) study on eastern Botswana, the role of secondary permeability is seen to be an important part of the aquifer hydrodynamics. Increasing attention is being given to the superimposed secondary effects of structural and tectonic influences on the primary hydraulic properties of the rock formations. For example, the hydrogeology of the Triassic sandstones of central England (Price, 1985), the chalk of eastern England (Nunn, et al., 1983), and the Tertiary limestones of Florida (Cederstrom et al., 1983), are now known to be strongly influenced by faults and their associated fracture systems.

In another example, Zacharias and Brutsaert (1988) show that while the recharge characterization of a watershed as a single unit may be a useful approximation, it can also have its limitations. The total groundwater discharge from a watershed is the <u>sum</u> of flow contributions from various sections along the aquifer such as infiltration at the head waters, transmission and storage along the channelways at the discharge areas, each of which have unequal behavioral properties, (i.e., the steeper parts of the drainage basin behave differently from those that are more gentle). Results of their studies show that secondary permeability greatly increases the total watershed base flow and the recharge calculations.

MODEL COMPONENTS

In order to explain the flow system of a particular aquifer with respect to an entire watershed, it is common to develop a simple conceptual model which describes the physical conditions of each of the components of the hydrogeologic cycle. This includes a description of the source of the water (usually precipitation), how the water moves to and within the watershed (infiltration and transmission), how the water is stored within the aquifer, and the nature of discharge from the system.

In the case of the megawatershed model, in addition to an evaluation of primary aquifer characteristics, results from descriptive site examinations, laboratory studies and computer modelling of fluid flow in fractured rock are also used to document the behavior of groundwater in all parts of the watershed.

Water Source

Although many exceptions exist, such as the potential Okavango Delta recharge of a Kalahari Megawatershed (Bisson, 1985), in most cases, groundwater has its direct source in precipitation. In many arid regions the average lowland or basin rainfall is usually low and the evaporation rate high. For example, in Libya rainfall varies from less than 25 to 400 mm per year, with potential evaporation rates at 1,700 to 6,100 mm per year, yet flow from a well field adjacent to springs in the Libyan desert has been measured at 250,000 cubic meters per day (45,000 gpm). In another case, La Moreaux et al. (1985) in their study of the Kharga Oases in the western desert of Egypt, found a mean annual rainfall of 1 mm, with potential evaporation rates similar to those cited above. Yet individual wells at the oases flowed at more than 15,000 cubic meters per day (2,700 gpm). Elsewhere, similar regimes of low rainfall, high potential evaporation, and anomalously productive springs have been noted as in the Sinai Desert (Issar, 1985).

Studies of some of these areas have stated that local recharge can not account for the measured discharge (Abufila, 1984; Ahmad, 1983). One possible answer is that recharge is coming from further away, in mountainous terrain. The "orographic effects" of mountainous terrains on rainfall can induce precipitation amounts which are considerably greater than in lowland regions (Figure 2). Given the distinct possibility that this meteoric water might enter subsurface fracture conduits connecting the mountains to the distant desert springs, then mountains may be a reasonable recharge source to consider. For example, the potential groundwater recharge rate from the Chad and Egyptian mountains to the Kufra and Sarir well fields (600 miles away) has been estimated at more than 70 million cubic meters per day (Alam 1989) -- considerably more than the two million cubic meters per day drawn from the well fields.

In some areas, where elevations and climate dictate, rain may occur as snow. Angelillo (1959) suggests that the snow pack may increase infiltration by decreasing rapid runoff (except during rapid spring melts). The times of slower melting would allow for constant subsaturation of the porous media below the snow and thus increase the infiltration rates. This would also increase the amount of water available for recharge.

It is also well established that over the past 200,000 years, the climate in many arid regions was different, with local rainfall rising to 1,000 mm instead of the current 100 mm or less. Alternating wet and dry climates were the rule during the Holocene (El-Baz, 1989). Geo-archaeological evidence indicates that the North African Sahara enjoyed wet climates 4,000 to 11,000 years ago, 20,000 to 35,000 years ago, about 60,000 years ago, about 140,000 years ago, and about 210,000 years ago. Rainfall during these periods would have been enough to support much vegetation and animal as well as human populations. Much of that water, which created river courses and vast lakes (El-Baz, 1988), would have been stored in groundwater aquifers.

Therefore, some of the water stored in the present day aquifers is likely to be paleowater. Issar (1985) found that the water from large springs in the Sinai Desert was 20,000 to 30,000 years old. La Moreaux (et al., 1985) proposed the same for water found at the Kharga Oases in Egypt.

The apparent age of such waters may also be due to the great distances that some of the water at these oases might have travelled (tens to hundreds of kilometers), along subsurface conduits, between source and spring (Abufila, 1984; Ahmad, 1983). The very slow natural velocity of water through an aquifer results in a major age difference along the length of the system. In effect, the age of the water coming out of desert springs is much older than the groundwater near the source of recharge.

We caution against establishing the presumption that recharge is not sufficient, or that the "paleowater" discovered in major desert basins will be "mined out" and not replenished. Before such a conclusion is made, the calculation of potential recharge must include more measurements of the possible increase in recharge due to (1) spatial and temporal variations i. 5.

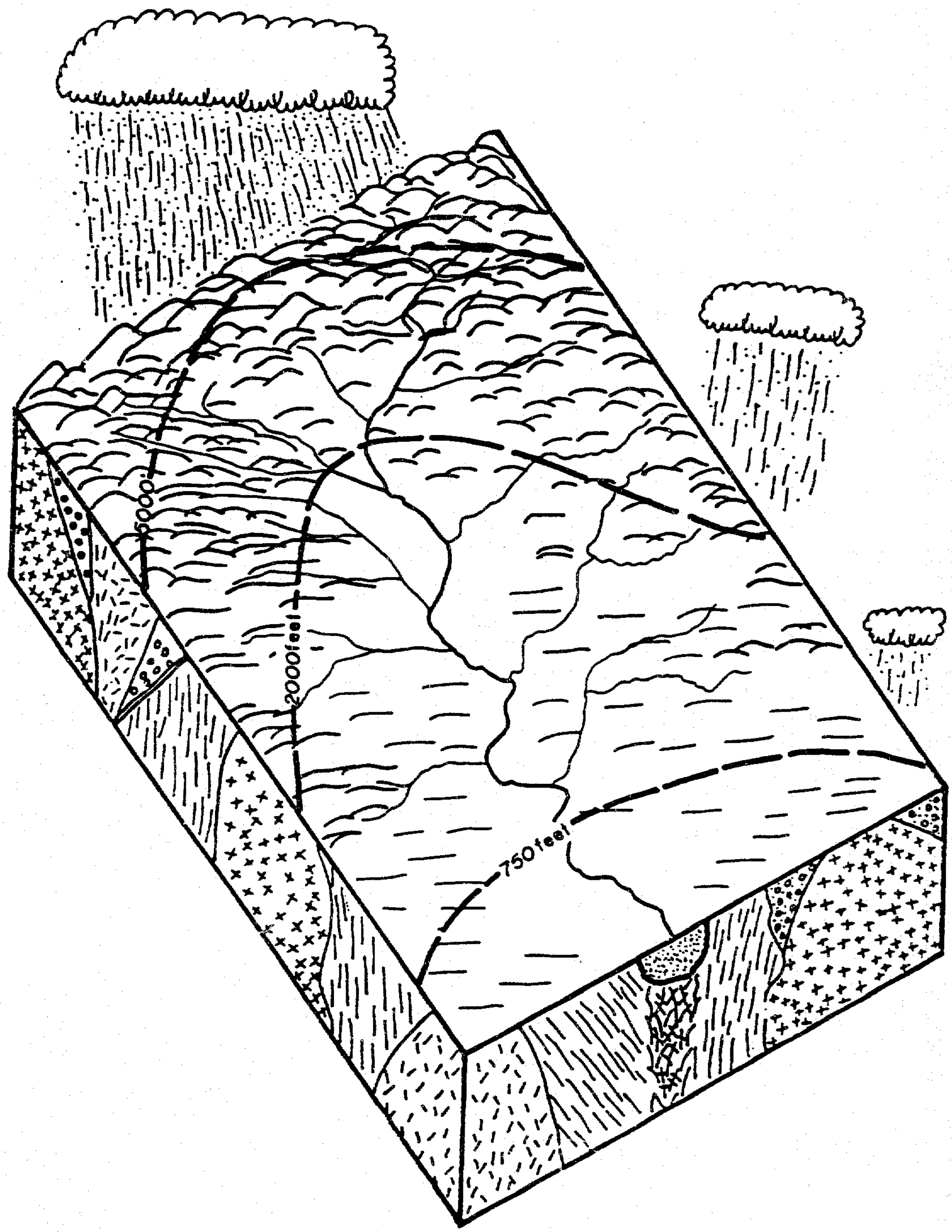


FIGURE 2: Orographic Effects On Precipitation Due To Topographic Variations In The Terrain.

precipitation versus the very limited baseline precipitation data of remote arid environments; (2) the effects of increased infiltration associated with zones of secondary permeability in mountainous areas; and (3) the effects of regional, increased transmissivity from enhanced secondary permeability imparted by fractures and faults. In addition, the induced infiltration effects on long-term, large scale pumping of wells must be considered as a probable outcome in the development of these resources.

Infiltration

An important part of a recharge estimation is related to the size of the catchment area (watershed) and the amount of water that is estimated to infiltrate into groundwater conduits. It is obvious that large catchment areas (>20,000 sq km) have the potential to yield more water for recharge (Figure 3). However, smaller basins (<1,000 sq km), in some cases, also have the potential to yield high grade water.

The potential for high-grade water yield is related to the permeability of materials directly underlying principal rainfall areas. This surface permeability strongly influences infiltration rates to unconsolidated and consolidated formations, with varying storativities and transmissivities, related both to primary and to secondary attributes of permeability.

Precipitation magnitude, an equally important factor, is spatially highly variable, often due to local terrain (elevation) effects. When natural conditions result in highly permeable materials (especially, fractured rock surfaces) being subjected to heavy precipitation events, as in many arid mountainous areas, the condition exists for substantial actual infiltration amounts in spite of high "potential evaporation" or other theoretical impediments to groundwater recharge.

The combination of these "remote-recharge" factors may account for the major fraction of available new water for arid areas megawatersheds. Of course, infiltration rates will vary with those physical and chemical qualities that control runoff and evaporation, including surface texture, porosity, degree of soil saturation, amount/type of vegetation, and slope. For example, if the surface texture is smooth with a low permeability, then runoff will be high and the amount of water that infiltrates will be small, even if the watershed is large (and vice versa).

In basins that contain fracture/fault zones (Figure 4), the infiltration rates are likely to be extremely variable. Rocks that are cut by these fracture/fault zones erode faster, leaving a highly irregular surface with large, polygonal, tubular, and disk-shaped voids. The largest frequency of these surface voids is generally adjacent to and within brittle fault zones. At some distance from these zones, the density decreases, the surface becomes much smoother, and the porosity decreases rapidly, so does the infiltration rate.

Often there is some interconnected permeability in the fractured zones with a much lower permeability in the surrounding rocks. It is possible that a low infiltration rate in the surrounding unfractured crystalline rock (less than .10 mm per day) exists along with a very high infiltration rate in the fractured rock (greater than 440 mm per day), as similarly estimated by Chow (1964). Fracture/fault zones often constitute local or regional topographic lows. This may result in a channeling effect, where water flows from smooth, impervious terrain into porous, fractured media.

These fracture zones of potentially high infiltration may occur in both non-porous (crystalline rocks) and porous media. The enhanced secondary porosity, rough surface texture, and increased transmissivity of fracture

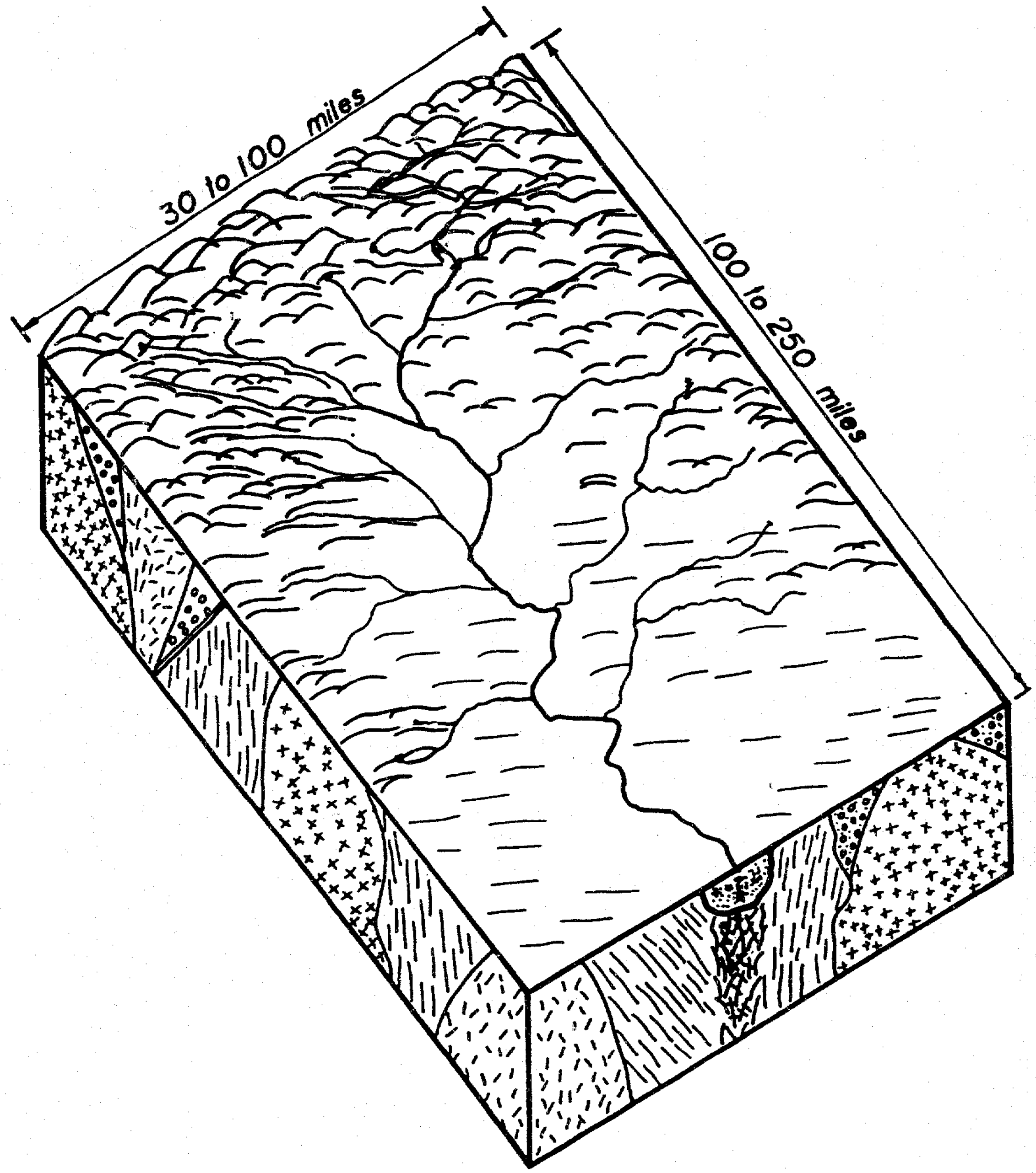


FIGURE 3: Drawing Illustrating the Catchment Area in a Large Basin.

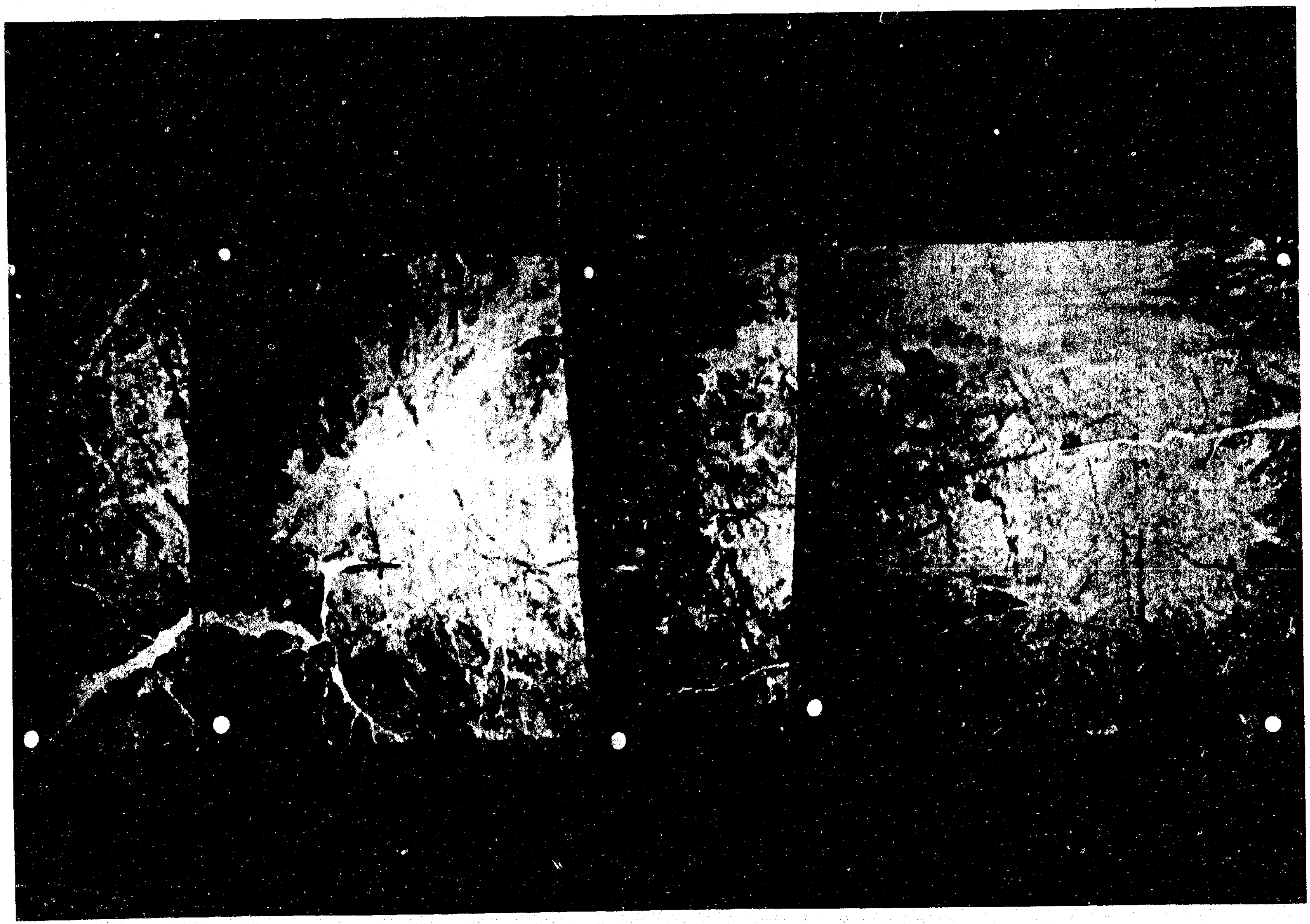


FIGURE 4: A Strip of Aerial Photographs of Fault-controlled Drainage in the Red Sea Province in Eastern Sudan.

zones may cause increases in infiltration rates over the surrounding host rock and allow more water to infiltrate into groundwater conduits. Assuming that the infiltration rates of the fracture zones are higher than those of the surrounding rock, the amount of water that is potentially available for recharge increases proportionally to the surface area of the exposed fracture zone. This effect may result in a multi-fold increase in the infiltration rate, over what would normally be calculated, without the effects of secondary permeability.

Transmission

In the megawatershed model, the subterranean faulted and fractured zones possess high infiltration rates and form three-dimensional polygonal drainage patterns with fractal properties and often have surface expression (Barker, 1988, Barbara and Rosso, 1989). The fractal character means that small-scale fractured rock and drainage patterns are reflections of larger-scale patterns that are similar in shape and orientation. Many of the smaller fractures observed in outcrop display shapes and orientations similar to those observed on a regional scale. The smaller features that help to increase infiltration may be linked to the larger structural conduits thus allowing a portion of rainfall that infiltrates at the head waters to be transmitted along subsurface conduits. Eventually some portion of this subsurface water will exit (discharge) at a spring or well down gradient. The channeling of groundwater into subsurface conduits, associated with linear fault/fracture zones, may often result in economic amounts of extractable groundwater.

Numerous studies have shown a positive relationship between fracture traces and lineaments and zones of increased well yields. Lueder and Simons (1962) presented some evidence that wells with relatively high yields in Alabama, are found close to lineaments, whereas wells with medium to low yields are more randomly distributed. Sonderegger (1970) reported that in northern Alabama, wells located on fracture traces have yields four to five times that of wells located off of fracture traces. Siddiqui and Parizek (1971) showed that of eighty wells sampled in central Pennsylvania, those located on fracture traces, assuming a zone of fracturing 10 meters across, had a median productivity 5.5 times greater than off-fracture trace wells, and 9.4 times greater yields than wells located at random. Cederstrom (1972), in relating drainage development to the regional fracture system in the Piedmont region, found that many valleys and valley intersections are fracture controlled (confirmed by Parizek, 1976). He indicated that five wells located on major fracture valley intersections yield 1 mgd each.

Faust et al. (1984), in their analysis of the Baca geothermal system in New Mexico calculated that water moved along fault systems and permeable horizons a distance of 20 miles and discharged along a fault at the Jemez springs. The calculated discharge was approximately 1.2 million gallons per day. Emery and Cook (1984) analyzed the results of test pumping a BCI Geonetics-sited production well in Connecticut, U.S.A., that intersected a fault zone in crystalline rock where the initial test yield was over 700 gallons per minute. Huntoon and Lundy (1979) found extremely high transmissivities associated with faults in the Casper aquifer in Wyoming. Discharges up to 1080 gallons per minute were measured along the faults. La Moreaux et al. (1985) measured a flow of 2,750 gallons per minute along faults through the Kharga Oases in Egypt. (Kohut et al. (1984) test pumped a well in fractured granitic rock at 250 gallons per minute and calculated a transmissivity of 6.3 x 10-4 m(2)/s.) Smith (1980) found high flow and transmissivities associated with fault zones in Lincolnshire aquifer in England. Flow was measured at 3,700 gallons per minute with transmissivities up to 6.9 m(2)/sec. In Italy, water flow from a fracture cutting a tunnel was measured at 9,500 gpm (with 882 psi) and a total flow into the tunnel from several fractures was measured at 32,000 gpm (World Water, June 1989).

From these studies it is clear that fracture/fault zones can transmit large quantities of water and in many cases contribute to the discovery of high grade water.

Tsang and Tsang (1987) studied a 14,000 square meter area of crystalline rock in Sweden and found that 50% of the total groundwater flow was accounted for by 3% of the area due to the preferential flow of water along open fractures zones. In addition, there is preferential flow <u>within</u> the individual fracture system. Moreno et al. (1988) studied the flow of groundwater within a single vertical fracture system and found that only 10 to 20 percent of the fracture actually participated in the groundwater flow. They pointed out that specific conduits were developed along interconnected disk-shaped voids between areas of fill and wall contact. It may be likely that 50% of the groundwater flows through fracture conduits (three-dimensional braided network, with fractal properties) that occupy less than 1% of the volume of the watershed. This is a strongly anisotropic feature in the subsurface flow and it has important ramifications with respect to groundwater exploration.

The anisotropy that is developed because of these preferential conduits strongly influences the behavior of groundwater in fractured terrain. As a result, zones containing high grade water can occur. But the target aquifer represents perhaps 1% of the total volume of the host rock region and thus presents a challenge to the exploration hydrologist.

The superposition of increased infiltration associated with zones of secondary porosity, open fracture conduits (increased transmissivity), increased drainage density, associated with fault/fracture zones and an increased gradient can result in an increased groundwater flow, and thus, increased recharge. Smith (1980) proposes the concept of "rapid recharge" when such open fracture systems are a dominant part of the groundwater flow. His study in Lincolnshire, England, revealed fracture zones of rapid flow with extremely fast response times. However, it is possible that a fraction of the groundwater recharge are conveyed to the system almost "instantaneously" in order to account for the observed events.

If the above observations of fast response times and anomalously high yields in fracture zones (high grade water) is reasonable, then we may assume some degree of fracture interconnectedness, along a reasonable gradient, from the zone of groundwater infiltration to the zone of groundwater discharge. The degree of the fracture interconnectedness and thus the flow through the subsurface system will vary due to many factors. The hydraulic conductivity of fracture systems is dependent upon the density of the fractures, the aperture of the fracture, the degree of roughness, the tortuosity (ratio of traveled path over linear path) the interconnectedness of the fractures and the hydraulic head. The number of rigorous studies on the fluid flow through highly fractured terrains over the length of a watershed is limited, but the following general observations can be made:

<u>Fracture Characteristic</u>	<u>Effect on Flow</u>
Fracture width-aperture	The permeability of smooth walled fractures is directly proportional to the cube of the fracture width (Sterns & Friedman, 1972)
Fracture density	Permeability increases as the fracture density increases (Sterns & Friedman, 1972)

Fracture Connectedness	The larger the connectivity of the fracture network and intersection of fractures, the greater the permeability

The density of fractures needed for flow to be established is called the percolation threshold (deMarsily, 1985). Throughout the length of a subsurface fracture conduit, many finite or discontinuous clusters of fracture zones would have to become connected at a level exceeding the percolation threshold. This would form a continuous fracture zone over the length of the watershed, with a relatively high transmissivity (Figure 5). In most fractured regions, the fracture density increases closer to a major structural weakness. As the fracture density increases and/or the ratio of joint length to joint spacing increases, so does the probability of fracture connectedness (Gale, 1982) and thus the probability of sufficient transmissivity.

Surface Roughness	The effects of roughness vary depending on the aperture. When the flow is nearly laminar, as within wide fractures, the effect is minimal (Moreno et al., 1988, Sterns and Friedman, 1972)
Tortuosity	The effects of tortuosity vary depending on the aperture. When the flow is nearly laminar, as within wide fractures, the effect is minimal (Tsang and Witherspoon, 1985).
Pressure Gradient/ Hydraulic Head	The more parallel the extensional fractures are to the gradient, the larger the permeability (Endo and Witherspoon, 1985; Sterns & Friedman, 1972; Gale, 1982).

The pressure is expressed as potential energy (e.g., pounds per square inch). The hydraulic head is defined at a point and is the measure of groundwater level using a piezometer, compared to a reference pressure and elevation. The hydraulic head (or pressure) is composed of a gravitational head due to change in elevation and a pore pressure due to the confining pressure imparted on the pore fluid.

In near surface fracture systems with wide apertures that are parallel to the gravitational gradient, it is likely that the pressure within that system will be dominated by gravity. This pressure will remain dominant until the confining pressure (of the rocks) exceeds the gravitational pressure (of the water).

In fractured, porous-medium aquifers at depth, the confining pressure (rock) may exceed the gravitational pressure (water). In these cases the pressure within the fracture/fault systems that are transmitting large volumes of water through the basin is increased by the confining pressure of the surrounding rocks as the pore fluid under pressure moves from the host to the fracture zone. The combination of increased confining pressure, increased gradient, and increased transmissivity could result in unusually high yielding "artesian" wells that could endure for centuries.

In summary, the fractured rock conduit that is likely to transmit large amounts of water will:

- have a high density of fractures;
- have fractures with wide apertures (extensional);
- be parallel to gravitational gradient;
- receive adequate recharge; and,
- be over-pressured

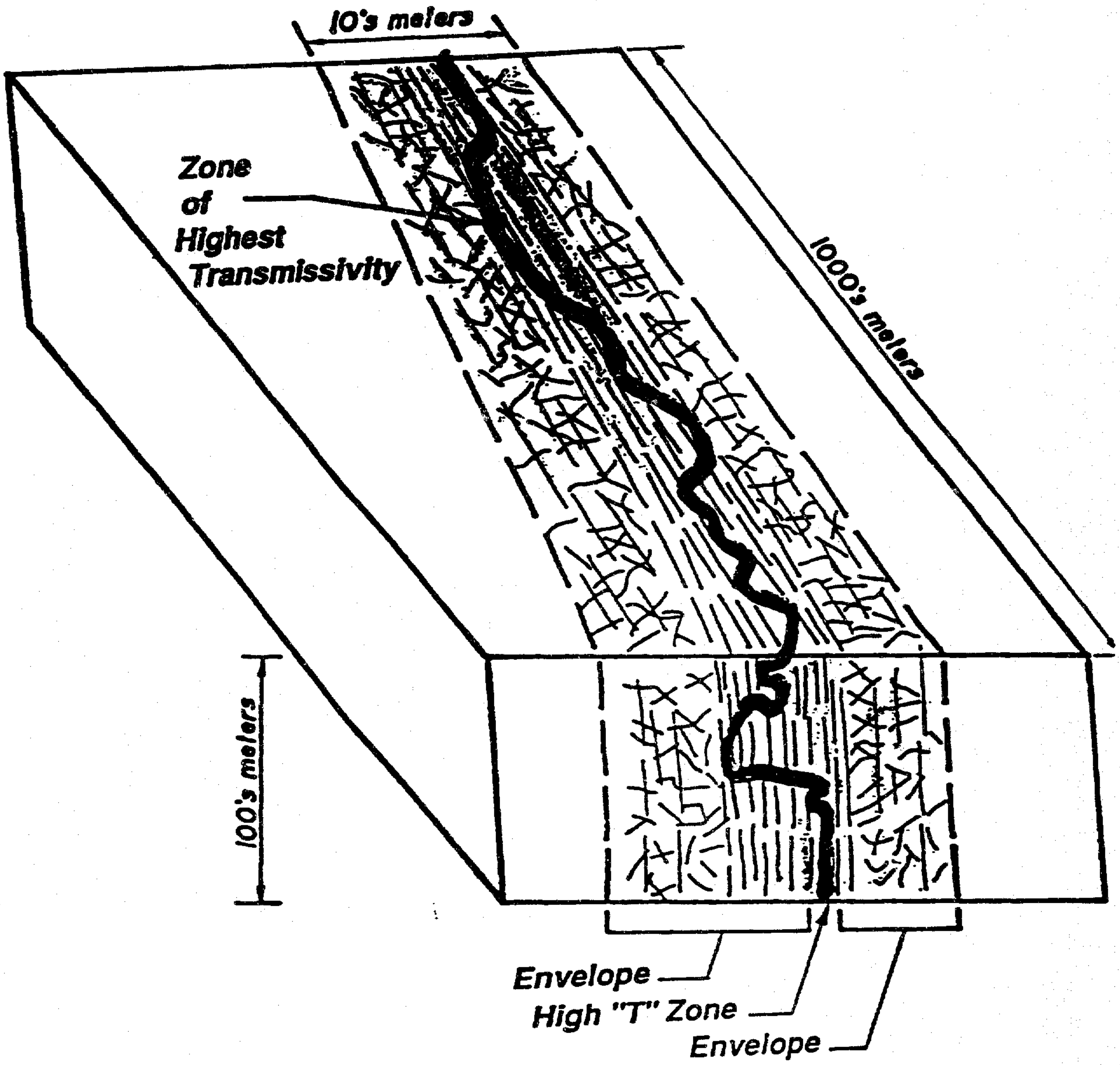


Figure 5. Detailed Illustration of a Fracture Zone Aquifer Consisting of a Highly Transmissive Zone and an Envelope with High Storativity.

When these conditions coexist, the subsurface fracture zones will serve as conduits for the transmission of high grade water along preferential zones that comprise a small percentage (one to three) of the total volume of material in the watershed. It is possible that the transmissivity along these conduits will be considerably higher (two to three times) than that normally calculated for permeable zones that do not have the overprint of a well developed secondary porosity.

Storage

The total yield (specific yield) from an aquifer is proportional to the amount of water held in storage, the amount of water transmitted (pumped) out of storage, and the rate of water replenishment (recharge). Discussion of the characteristics of a fracture zones with high transmissivities also applies to the analysis of specific yield. A unique characteristic of fracture zones is that they may contain both a zone of high transmissivity with low storativity (in the fracture conduit), and a zone of lower transmissivity with higher storativity (enveloping the fracture conduit) (Figure 5).

The previous discussion indicates that open fracture zones parallel to the hydraulic gradient are capable of transmitting large quantities of water and that they may also be recharged rapidly. This occurs within the fracture conduit. The fracture envelope around this conduit is less transmissive but serves as storage that replenishes the open conduit and is also replenished by this conduit (Figure 5). These characteristics of a continuous bedrock aquifer (composed of the fractured rock adjacent to a highly transmissive zone, either discreet or in combination with alluvium or some other porous medium (Figure 6) define an important part of a megawatershed groundwater exploration target.

In addition, in the vicinity of the target aquifer, the fracture should have a moderate non-dispersion factor. This means that the width of the aquifer and its associated conduits and micropathways is not so large as to disperse the amount of available recharge over a broad area composed of discontinuous aquifers. A large dispersion factor would disperse the available resource and decrease the potential yield of any single target aquifer. Conversely, a small dispersion factor, where the extent of the aquifer is narrow, severely limits the potential storage and yield of the target aquifer.

In most cases defining the groundwater resource and its potential for long term sustainable yield will require more sophisticated modelling than that applied to porous media. Some form of multiple porosity model may need to be applied due to the following:

(1) the conduit of the fracture zone will have porosity and transmissivity values that differ from the surrounding materials;

(2) the fracture zone envelope will have values significantly different from the host rock or the conduit; and

(3) both host rock and fracture zone porosity (conduit and envelope) will be significantly different from that of overlying sediments.

In such regions, the application of a double porosity model might be the best way to explain the flow characteristics. The open conduit would be characterized by a rapid flow and a rapid recharge whereas the surrounding fracture envelope (and the alluvium) would be characterized by much lower transmissivity values but greater storativity.

For a fractured porous medium, Gale (1982) favors a "coupled discrete-fractured porous medium model" where faults and shear zones are defined as

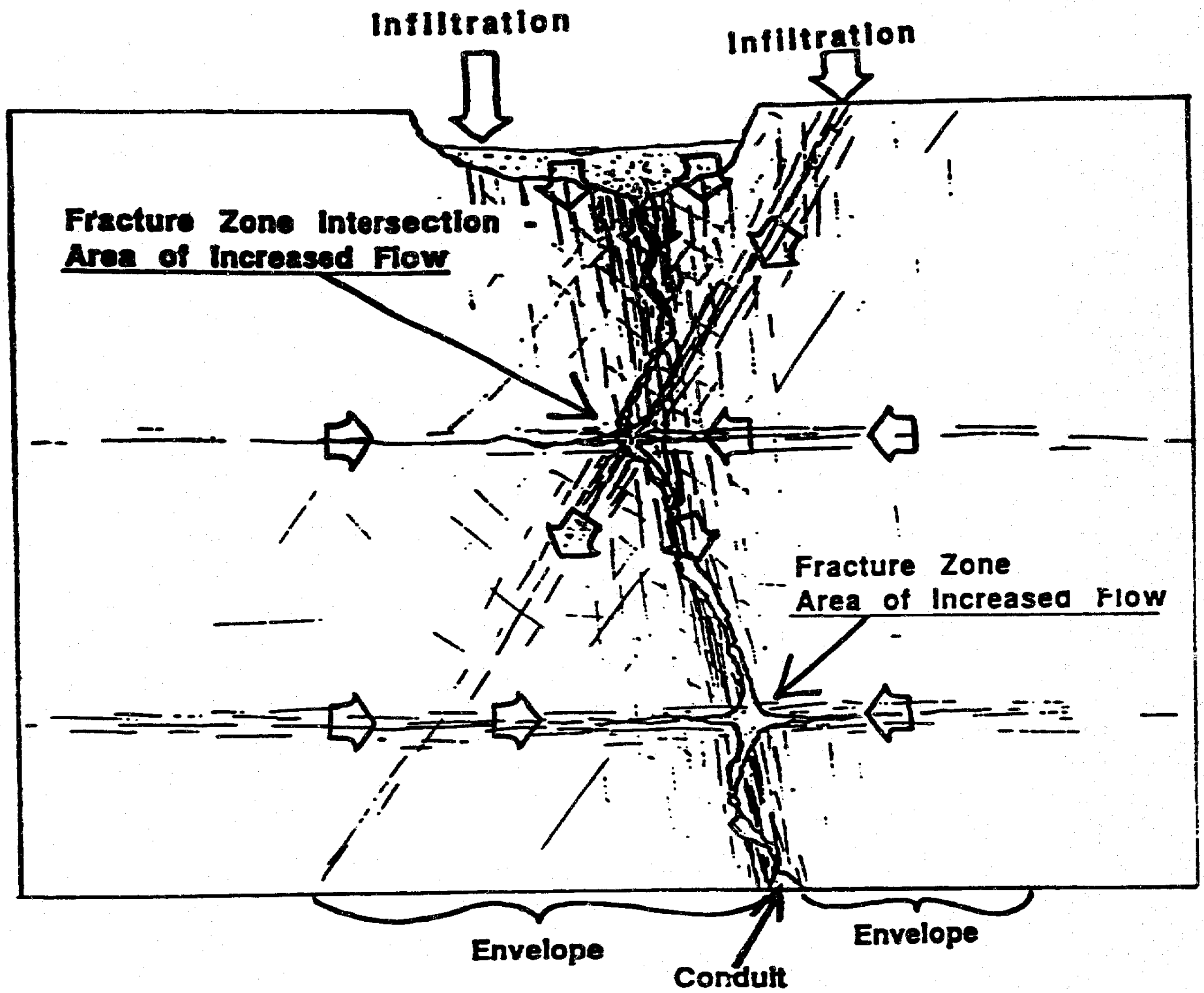


Figure 6. Cross-sectional View of a Fracture Zone Aquifer Illustrating the Relation of Flow to Fracture Intensity. Arrows Show Direction of Groundwater Flow. Dominant Flow is Perpendicular to the Page.

individual features, the permeability of the host rock is a feature and the joint characteristics another feature. For modeling a groundwater storage unit as illustrated in Figure 7, some modification of Gale's approach may be warranted. We propose using a discrete, individual characterization approach, for the conduit and the fracture zone, and an averaging or continuum approach for the host rock and the sediment. In addition, the model will define the interactions between media of differing porosity.

The model should be used to characterize the partial groundwater contributions to the total potential sustainable yield from each of the following:

(1) the sediment aquifer;
(2) the conduit within bedrock;
(3) the fracture envelope within bedrock; and
(4) the interplay between these three features with regard to the pumping rate and the recharge.

Further research will shed light on the characteristics of various portions of these complex aquifer characteristics and how they may change as the hydrogeologic parameters vary, and how these changes effect the potential sustainable yield of the resource.

From experience, we know that these fracture-controlled aquifers can exhibit large variations in quantities and qualities of water. The primary goal is to produce the greatest yield of the cleanest water with the lowest economic cost and environmental impact. The megawatersheds model (which attempts to address the complexities of bedrock aquifer systems), provides the groundwater explorationist with a qualitative perspective. Ongoing development and revisions of the model will better incorporate further on-site evaluations of watersheds and possibly include some computer modeling as data is compiled over time.

Groundwater Discharge

The concept of high grade water associated with fracture zones is further supported by the occurrence of large fresh water springs at the distal ends of basins. These springs may occur on the coast, as in Libya, or they may occur in a rift valley as in the Sinai. As stated above, the flow rate in either case is anomalously high. The springs may also occur offshore. Large fresh water springs are known off the Mediterranean and Red Sea coasts of Africa. In many other coastal regions of the world, from the American coasts of Florida and California to the Arabian Gulf, large amounts of fresh and brackish water have been encountered.

This suggests that there is a connection between basin edge occurrences of high grade water and a highly transmissive fracture zones that are connected to drainage basins. This is supported by the fact that high grade water cannot be accounted for using standard local recharge and primary porosity models (Issar, 1985). The high grade water might be induced along zones of higher permeability, e.g. fault and fracture zones, and these zones might be connected to broader areas of recharge either through fractured rock alone or in combination with a rock unit possessing primary porosity.

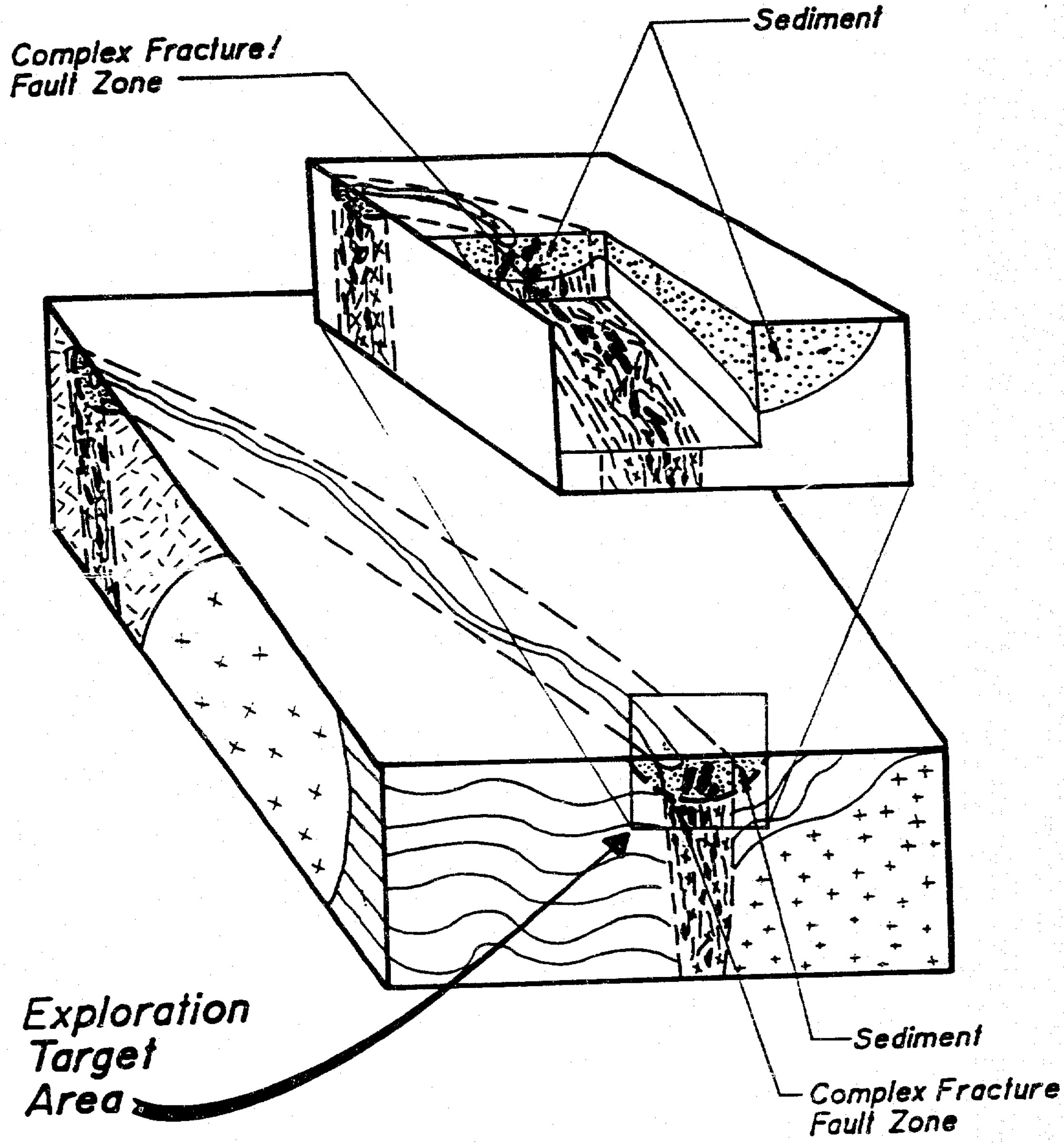


FIGURE 7: Illustration of an Alluvium/Fracture Trap Showing Location of a Major Fracture/Fault Zone with Alluvium Acting as a Water Trap. Note the Complex Nature of the Fault/Fracture Zone.

HYPOTHETICAL MODEL COMPARISON
EGYPT/SUDAN RED SEA REGION

General Assumptions

The megawatershed model dictates that certain hydrogeologic assumptions apply due to the effects of secondary porosity and permeability. The following comparison of three different models for a proposed wellfield, with natural environmental characteristics found in the narrow, coastal plain of the arid Red Sea Provinces of Sudan and Egypt, will help to illustrate these assumptions and the resultant order of magnitude difference of aquifer characteristics.

The watershed example for these model comparisons is a 300 square km basin with 150 mm average rainfall (leanest in the mountains), very little vegetation, soil or weathered rock cover, over an essentially exposed crystalline rock terrain. Alluvium is confined to "pockets" in the mountains, plus along certain reaches of wadis and in alluvial fans between mountains and sea coast. The three models are based on different hydrogeologic and geologic assumptions. The general model assumptions are as follows:

Model 1: Economically Accessible groundwater is stored only in alluvium in the coastal plain and fractured rock has a negligible effect on groundwater storage or flow. Recharge is limited to overland flows that extend beyond the mountains and infiltrate into coastal alluvium. Direct mountain recharge is not significant.

Model 2: Economically Accessible groundwater is stored in alluvium and, locally (within 100 m of the well), in fracture zones. These local fractures contribute minimally to storage and, at best, may simply enhance local groundwater flow efficiency into a bedrock well.

Model 3: Economically Accessible groundwater storage and flows are strongly influenced by a regionally extensive network of subsurface fractures that extend essentially throughout the basin (Figure 8) and are largely in hydraulic contact with overlying alluvial deposits in the mountains, while possessing confined and semi-confined aquifer characteristics in the coastal plains. Recharge from mountain rainfall is assumed to contribute directly to this "megawatershed" (Figure 9).

Each of these models attempts to describe the nature of the aquifer connected to strategically located well fields. The values calculated for Models 1 and 3 are considered minimum and maximum values respectively, given that:

Catchment area	300 sq. km
Average annual precipitation	150 mm
Total annual rainfall	45 million cu. meters

Wellfield Recharge Estimations

In this arid environment, a large part of the hypothetical 45 million cubic meters of annual rainfall evaporates or becomes part of the runoff associated with flash floods. Part of the precipitation infiltrates into the subsurface, is transmitted to the aquifer and to economically accessible well fields near the coast. Models 1 and 2 assume that the alluvium is the only place where significant infiltration, transmission and storage can occur and that only local, coastal, rainfall and overland flooding contribute to recharge. Because of the limited areal extent and thickness of the alluvium and the assumed minor role of local fracture networks in Models 1 and 2, the net percent of rainfall contributed to infiltration is low (1 to 3%).

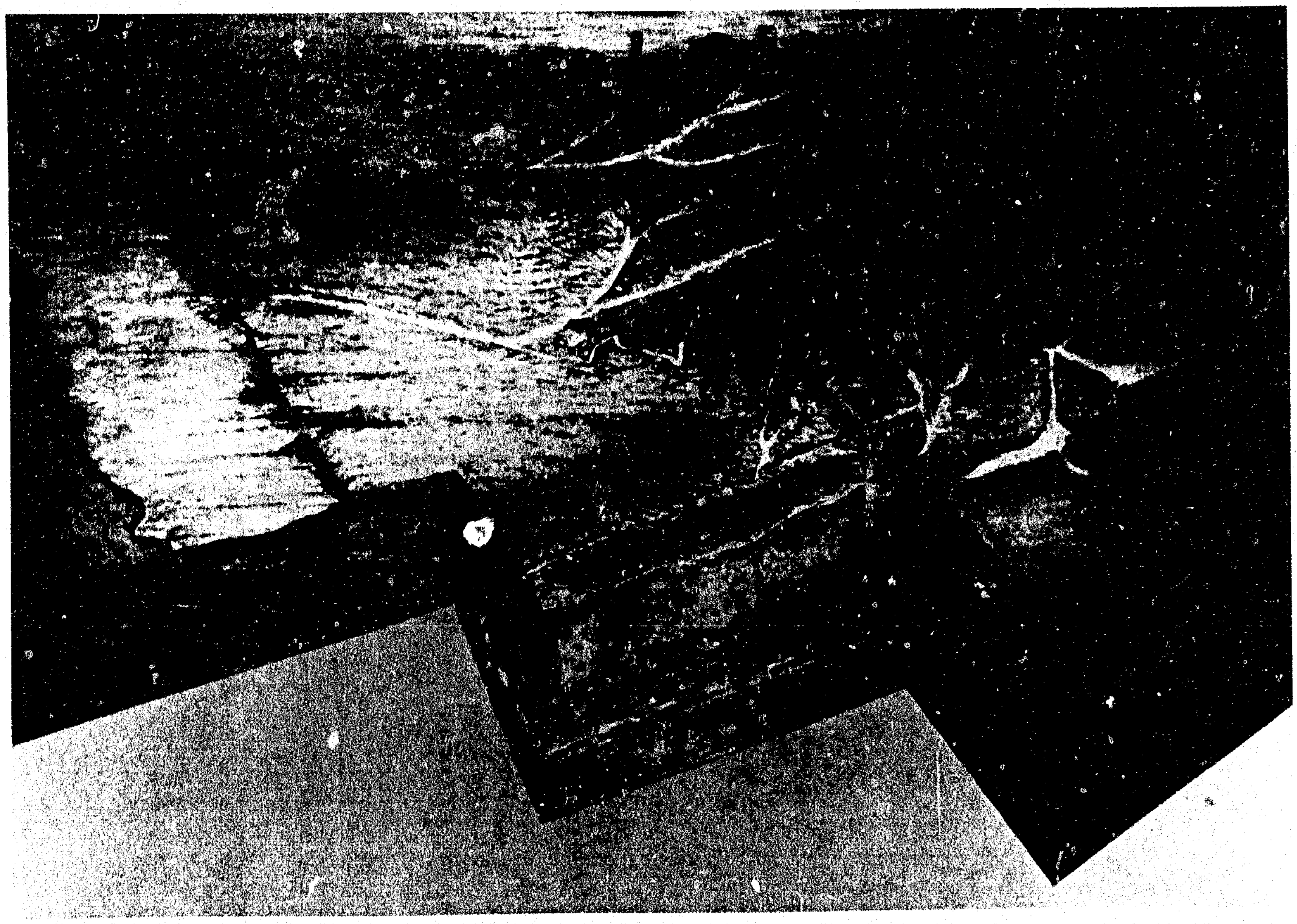


FIGURE 8: Perspective Illustration of the Megawatershed Model Applied in the Red Sea Province of Sudan. Arrows Indicate Overland and Underground Flow Paths.

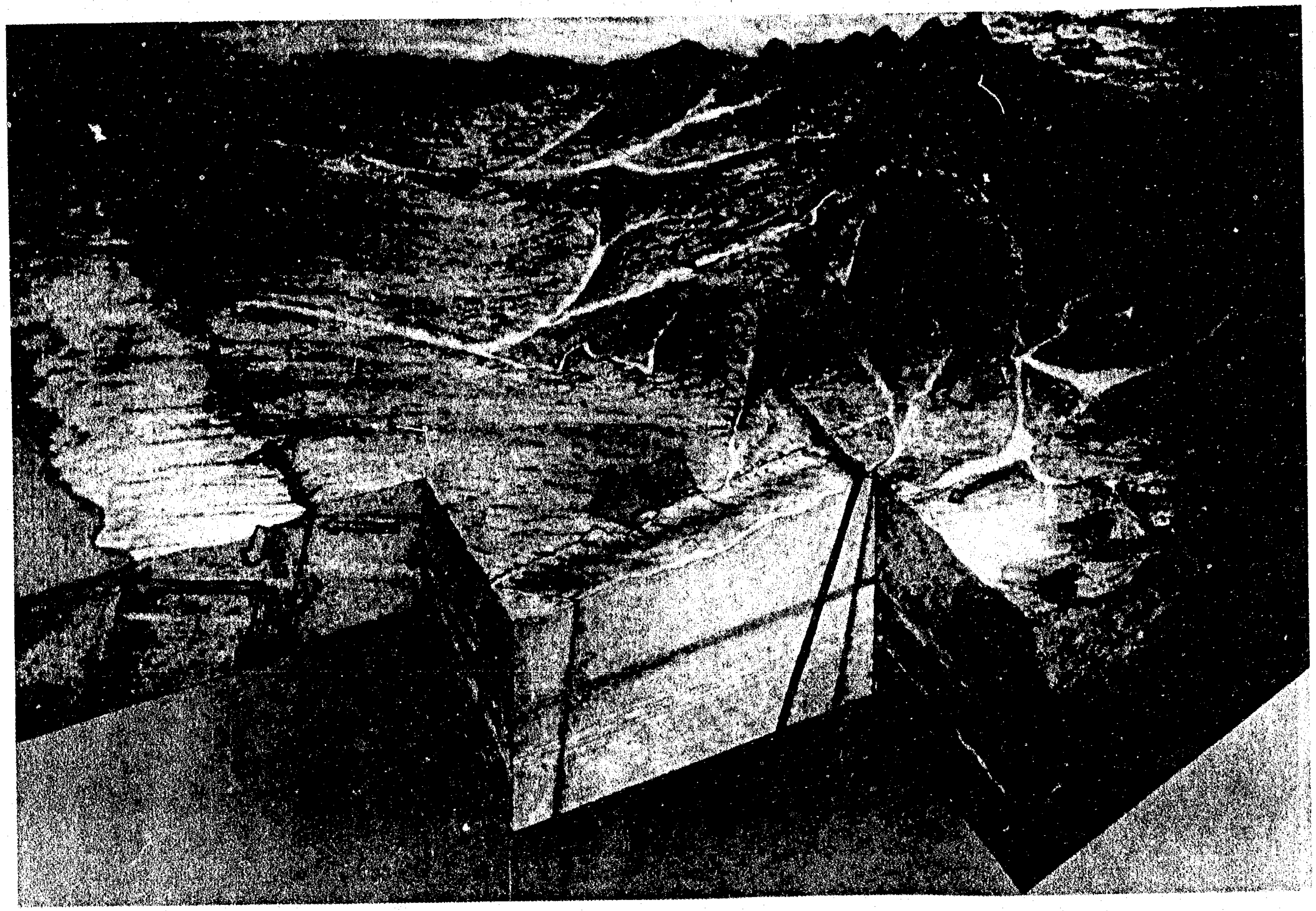


FIGURE 9: Perspective Illustration of the Megawatershed Model Applied in the Red Sea Province of Sudan. Arrows Illustrate Mountain Recharge to Fracture Systems and Alluvial Storage.

Further, once the water becomes part of the subsurface, it must be transmitted to the aquifer at the target well fields, if it is to be considered part of the potential yield calculations. The alluvium is considered in all three models to be generally of uneven thickness and surficial groundwater is, in some locations, forced nearer to the surface causing large amounts to evaporate. In addition, some groundwater stays trapped within the alluvium and is not transmitted to the well sites.

Given the constraints of Model 1, estimates of 5 to 10% transmission of infiltrated water to the well sites are considered reasonable by the authors.

In Model 2, a slight increase of .5% is added due to the influence of local fractures.

In Model 3, the effects of secondary porosity and permeability over much of the catchment area result in considerable increases in the estimates of infiltration, transmission and storage of groundwater. The numbers below illustrate this:

Hydrogeologic Parameters

	Infiltration	Transmission	% Rainfall	Cubic M/year
Model 1	1 - 3%	5 - 10%	.05 -.3%	2.25 x 10(4) to 1.35 x 10(5)
Model 2	1 - 3%	5.5 - 10.5%	.055-.315%	2.4 x 10(4) to 1.4 x 10(5)
Model 3	3 - 9%	10 - 30%	.6 - 3%	2.7 x 10(5) to 1.35 x 10(6)

The result of these calculations, expressed as average annual active recharge, are summarized below:

Potential Recharge Comparison

Model 1	370 m(3)/day	68 gpm
Model 2	384 m(3)/day	70 gpm
Model 3	3,700 m(3)/day	678 gpm

From these hypothetical model comparisons, it is clear that Model 3 provides an order of magnitude larger amount of recharge than Models 1 or 2.

Storage Calculations

In all these models, calculations of storage assume a continuous aquifer over which average values of effective porosity can be extrapolated.

The alluvial storage in Model 1 is limited to an already confined surface drainage, extending from the base of the mountains, 20 km downstream to the proposed well fields sites. The alluvium is considered to average 10 m in thickness and to average 30 m in width. The porosity is 0.2.

In Model 2, the alluvial storage remains as in Model 1, but is supplemented by a local fracture system, consisting of two intersecting fracture zones, each 100m long, 10 m wide and 100 m deep and one horizontal fracture (200 x 100 x 1m), with an average porosity of 0.05.

In model 3, the alluvium is also considered as potential storage as in Models 1 and 2, but this is supplemented by a fracture zone network consisting of three vertical fracture zones extending nearly the length and width of the overall catchment area and one extensive horizontal fracture zone at depth. The width of each vertical zone is 20m, depth 200 m and combined length of 30 km. *For purposes of simplicity, the considerable impact of the active mountain alluvial recharge and storage is ignored in this Model*. The dimensions of the horizontal zone are 20 km x 5 km x 1 m. All fracture zones have an average porosity of 0.05.

Potential Storage Comparison

	Volume (m3)	Porosity	M(3)	Total M(3)
Model 1	A- 6.0 x 10(6)	.20	1.2 x 10(6)	1.2 x 10(6)
Model 2	A- 6.0 x 10(6)	.20	1.2 x 10(6)	1.21 x 10(6)
	F- 0.22 x 10(6)	.05	11000	
Model 3	A- 6.0 x 10(6)	.20	1.2 x 10(6)	9.2 x 10(6)
	F-160.0 x 10(6)	.05	8.0 x 10(6)	

The above calculations predict the maximum amount of water that could be in storage under ideal conditions for each model.(1) It is likely that both the alluvium and the fracture networks are not homogenous and are not hydraulicly connected in a uniform manner. This means that a part, perhaps 50% of the groundwater in storage, is not available for easy extraction at the given well site. This results in potential yield calculations as follows:

	Transmittable Storage	Potential Yield	
	M(3)/Year[1]	M(3)/Day	GPM
Model 1	6.0 x 10(5)	1,644	302
Model 2	6.05 x 10(5)	1,650	304
Model 3	4.60 x 10(6)	12,600	2,311

The most important aspect of the megawatershed model is that it predicts an order of magnitude higher groundwater flow at a site that fits the parameters of the model. Thus, it predicts the occurrence of high grade water.

These model comparisons only serve as an example of the implications of the inclusion of fractured rock porosity and permeability in basin model calculations for safe yields. The procedure could be applied to any area

1/ Note: Model 3 exception of mountain alluvium.

that contains surface and subsurface drainage controlled by fault/fracture zones. The comparisons also support the original premise of the megawatershed model, which describes the boundary conditions related to the occurrence of high grade water associated with a watershed-wide three dimensional fracture network.

The exploration significance of the model is that it can be used as a pathfinder, to lead groundwater exploration teams to previously unsuspected targets that could yield large amounts of "high grade" water.

CONCLUSIONS

The key features of the megawatershed model are as follows:

- In arid coastal regions, bedrock-transmitted mountain precipitation, resulting from orographic effects, may considerably increase the amount of water available down-gradient over what is available from local coastal plain recharge.

- Zones of highly fractured bedrock terrain possess infiltration rates higher than the surrounding materials.

- High fracture density and linear extent of these zones may contribute significantly to increased potential groundwater recharge.

- Surface areas of alluvium with high infiltration rates may connect with highly permeable fracture/fault zones.

- These fracture/fault zones may interconnect over large areas and thus provide a larger subsurface catchment area from which water flows, thus increasing the potential recharge. This may be represented as a surface expression of rectilinear drainage.

- The fracture conduits containing high grade water are restricted in lateral extent (width), are non-uniform, and comprise a small percentage of the total subsurface volume.

- The envelope (and any hydraulicly connected sediments) surrounding the fracture conduit serve as storage.

- The best fracture/fault zones are those that have a high density of wide fractures parallel to a reasonable hydraulic gradient.

- Highly favorable targets are those that contain geologic formations with primary porosity in hydraulic connection with fracture/fault zones and connected to the main source of recharge.

Exploration for, discovery of, and accurate mapping of these anomalous zones of groundwater flow is a task that requires the combination of many disciplines; remote sensing, climatology, geomorphology, structural geology, hydrogeology and geophysics. Conceptual models, such as the megawatersheds model, help the exploration team to apply these disciplines in an efficient manner while increasing their probability of success.

ABOUT THE AUTHORS

Robert A. Bisson is the founder and Chairman of the Board of Directors of BCI Geonetics, Inc., and is the principal architect of the firm's integral systems approach to natural resource exploration and management, trademarked the "MESA" Program.

Since 1972, Mr. Bisson has led BCI's explorationists in mineral and water exploration programs in forty U. S. states and in eight Mid East and African countries. Before founding BCI, Mr. Bisson participated in privately-financed oil and gas exploration programs in several west African states, with a focus on coastal Nigeria and the Camerouns.

In addition to economic mineral exploration activities, Mr. Bisson has participated in project management and senior technical roles in more than sixty environmental projects, including power plant siting and impact analysis, (hydro-, fossil-, and nuclear-fueled), oil refinery site evaluations, seweage treatment plan watershed impacts, highway impacts, and non-point water pollution studies.

Mr. Bisson has published numerous papers on the subject of groundwater exploration and regularly lectures on the subject to a variety of academic and professional audiences.

****

Dr. Farouk El-Baz is Director of the Center for Remote Sensing at Boston University, Boston, Massachusetts. From 1982 to 1986 he was Vice President for Science and Technology at Itek Optical Systems, a division of Litton Industries, in Lexington, Massachusetts. Starting in 1973 and until he joined Itek, Dr. El-Baz established and directed the Center for Earth and Planetary Studies at the National Air and Space Museum, Smithsonian Institution, Washington, D. C. In addition, between 1978 and 1981, he served as Science Advisor to the late President Anwar Sadat of Egypt.

From 1967 through 1972, Dr. El-Baz worked with Bellcom and Bell Laboratories, Washington D.C., as Supervisor of Lunar Science Planning and Lunar Exploration. During these six years, he participated in the planning and evaluation of NASA's Lunar Orbiter program and was a member of the science support teams of the Apollo lunar missions. He served as Secretary of the Site Selection Committee for the Apollo lunar landings, and was Chairman of the Astronaut Training Group for Orbital Science and Photography. He was also Principal investigator for the Earth Observations and Photography Experiment on the Apollo-Soyuz Test project in 1975.

Dr. El-Baz has published over two hundred scientific papers and authored eight books.

REFERENCES

Abufila, Taher M. (1984), *A Three-Dimensional Model to Evaluate the Water Resources of the Kufra and Sarir Basins, Libya*.

Ahmad, Moid U. (1983), *A Quantitative Model to Predict a Safe Yield for Well Fields in Kufra and Sarir Basins, Libya*.

Alam, M. (1989), Water resources of the Middle East and North Africa with particular reference to deep artesian groundwater resources: unpublished report to The World Bank.

Angelillo, O.R. (1959), Replenishing Source of Waters Flowing Through Rock Fissure Aquifers (unpublished manuscript). Jan. 20, 1959.

Badgely, P.C., 1965, Structural and Tectonic Principals: New York, Harper and Row, 521 p.

Barbara, P.L. and Rosso, R., 1989, On the Fractal Dimension of Stream Networks.

Barker, J.A. 1988, A Generalized Radial Flow Model for Hydraulic Tests in Fractured Rock: Water Resour. Res.

Bisson, R.A., Unpublished research, 1985-89, and unpublished confidential report to commercial client, titled: *Feasibility Study on the Development of Groundwater Resources in Southern Africa*, 1985.

Buckley, D.K., and P. Zeil, 1984, The character of fractured rock aquifers in eastern Botswana. *Challenges in African Hydrology and Water Resources* (*Proceedings of the Harare Symposium*), IAHS Publication no. 144, pp.25-36.

Cederstrom, D.J. 1972, Evaluation of Yields of Wells in Consolidated Rocks, Virginia to Maine: U.S.G.S. Water Supply Paper 2021, 38p.

Cederstrom, D.J., E.H. Boswell and G.R. Tarver, 1983, South Atlantic-Gulf Region· in, Todd, D.K., 1983, *Ground-Water Resources of The United States*, Premier Press, California.

Chow, V.T. (1964), Handbook of Applied Hydrology: McGraw Hill, N.Y.

Cloos, H., 1948, The Ancient European basement blocks-preliminary note: Trans. Am. Geophys. Union 29, v. 1, p. 1748-1759.

Dana, J.D., 1847, Origin of the Grand Outline Features of the Earth: Am Jour. Science, Sec. 2, v. 3, p. 381-398.

deMarsily G. (1985), Flow and Transport in Fractured Rocks: Connectivity and Sale Effect: in Hydrology of Rocks of Low Permeability: Intern. Assn. Hydrologists, V.XVII, Pt. 1, p. 267-277.

El-Baz, F. (1988), Origin and Evolution of the Desert, *Interdisciplinary Science Reviews*, Vol. 13, No. 4, pgs. 331-347.

El-Baz, F. (1989), Monitoring Lake Nasser by Space Photography. *Remote Sensing and Large-Scale Global Processes* (Proceedings of the IAHS Third International Assembly. Baltimore, Maryland, May 1989). IAHS Pub. No. 186, p. 177-181.

Emery, J.M. and Cook, G.W. (1984), A Determination of the Nature of Recharge to a Bedrock Fracture System (results of testing a BCI Geonetics, Inc. production well at Putnam, Connecticut, U.S.A.): paper presented at the National Water Well Association groundwater conference, Newton, Mass., July 23-24.

Endo, H.K. and, Witherspoon, P.A. (1985), Mechanical Transport and porous media equivalence in anisotropic fracture networks: in Hydrology of rocks of low permeability Intern. Assn. of Hydrologists, V.XVII, Pt. 2, p.527-537.

Faust, C.R., Mercer, J.W. and Thomas, S.D. (1984), Quantitative Analysis of Existing Conditions and Production Strategies for the Baca Geothermal System, New Mexico: Water Resources Research, Vol. 20, #5, p. 601-618

Gale, S.E. (1982), Assessing the Permeability Characteristics of Fractured Rock: G.S. A. special paper 189, p. 163-181

Henderson, G., 1960, Air-photo lineaments in Mpanda area, Western Province, Tanganyika, Arifa: A.A.P.G. Bull., v. 44, No. 1, p. 53-71.

Hilgenberg, O.C., 1949, Die Bruchstructur der Sialischen Erdkruste: Akademie-Verlag, Berline, Germany, 106 p.

Hobbs, W.H., 1911, Repeating patterns in the relief and in the structure of the land: Geol. Soc. America Bull., v. 22, p. 123-176.

Hopkins, W. (1835), *Researches in Physical Geology*.

Huntoon, P.W. and Lundy, D.A. (1979), Fracture-Controlled Groundwater Circulation and Well Siting in the Vicinity of Laramie, Wyoming: Groundwater, V. 17 # 5, p. 463-469.

Issar, A. (1985), Fossil Water Under the Sinai-Negev Peninsula: Scientific America, V. 253, #1, p. 104-111.

Kohut, A.P., Foweraker, J.C., Johanson, D.A., Tradewell, E.H. and Hodge, W.S. (1984), Pumping Effects of Wells in Fracture Granitic Terrain: Groundwater, V. 21, p. 564-572.

La Moreaux, P.E., Memon, B.A., and Hussein I (1985), Groundwater Development, Oasis, Western Desert of Egypt:
A Long-Term Environmental Concern: Environ. Geol. Water. Sci., Vol. 7, #3, p. 129-149

Lueder, D.R. and Simons, J.H., 1962, Crustal Fracture Patterns and Groundwater Movements: White Plains, N.Y., Geotechnics and Resources Inc. Report to Bureau of State Services, U.S. Dept. of Health, Educ. and Welfare, Final Report of Grant WP-53, 148p.

Mollard, J.D., 1957, Aerial mosaics reveal fracture patterns on surface materials in southern Saskatchewan and Manitoba: Oil in Canada, v.a., p. 26-50.

Moreno, L., Tsang, Y.W.; Tsang, C.F., Hale, F.V. and Neretnieks, I. (1988), Flow and Tracer Transport in a
Single Fracture: A Stochastic Model and its Relation to Field Observations: Water Resources Research, V. 24, #12, p. 2033-48

Nunn, K.R., Barker, and Bamford, D. (1983), In Situ Seismic and Electrical Measurements of Fracture Anisotropy in the Lincolnshire Chalk: Q.J. Engl Geol. London, Vol. 16, pp. 187-195

Parizek, R.R., 1976, On the Nature and Significance of Fracture Traces and Lineaments in Carbonate and Other Terrains: in proceedings of Karst Hydrology and Water Resources Symposium, Dubrovnik, Yugoslavia; June 2-7, 1975, Water Resources Pub., p. 47-108.

Price, M. (1985), Introducing Groundwater: Allen & Unwin, London

Siddiqui, S.H. and Parizek, R.R. (1971), Variations in Well Yields and Controlling Hydrogeologic Factors: in College of Earth and Mineral Science, Mineral Conservation Series Circular 82, Penn. St. Univ., p. 87-95.

Smith, E.J. (1980), Spring Discharge in Relation to Rapid Fissure Flow: Groundwater, Vol. 17, #4, p.346-350.

Sonderegger, J.L., 1970, Hydrogeology of Limestone Terraces -Photogeologic Investigations: Geol. Surv. of Alabama, NTIS PB-198, 27p.

Sterns, D. W. and Friedman, M. (1972), Reservoirs in Fractured Rock: AAPG Memoir #16, p. 82-106.

Tsang, Y.W. and Tsang, C.F. (1987), Channel Model of Flow Through Fractured Media: Water Resources Research, V. 23, p. 467-479.

Tsang, Y.W. and Witherspoon, P.A. (1985), Effects of Fracture Roughness on Fluid Flow Through a Single Deformable Fracture: in, Hydrology of Rocks of Low Permeability, Intern. Assn. of Hydrologist, V. XVII, pt. 2, p. 683-694

World Water, June, 1989, "Tunnel Collapse Shows New Water Supply,", Vol. 12, No.4.

Zecharias, Y.B. and Brutsaert, W. (1988), Recession Characteristics of Groundwater Outflow and Base Flow From Mountainous Watersheds: Water Resources Res., Vol. 24, #10, P. 1651-58.

91

APPENDIX II
Somalia Test Well Results

197663 TRANSCEN

MSG DD362

TO: ROBERT BISSON

FROM: LOUIS L. MITCHELL, CEO

TRANSCENTURY CORPORATION

DATEC NOV 20, 1986

I HAVE JUST RETURNED FROM SOMALIA AND AM ABLE TO CONFIRM SUCCESS OF THE FIRST OF TWO TARGET AREAS, WITH INITIAL TESTING OF MORE THAN 200 GPM FROM EACH OF THREE WELLS. I CAN ALSO CONFIRM THROUGH INFORMATION FROM MY ASSOCIATES THAT TWO FURTHER WELLS IN THE SECOND TARGET AREA HAVE BEEN TESTED AT 200 GPM.

WITH THESE EXTREMELY PROMISING ACHIEVEMENTS, WE ARE PRESENTLY PURSUING IMMEDIATE FUNDING FROM EUROPEAN ECONOMIC COMMISSION THROUGH THE UNITED NATIONS HIGH COMM. FOR REFUGEES IN ORDER TO COMPLETE PRODUCTION FACILITIES AT TARGET AREA NO. 1 IN THE CITY OF BOROMA. USING YOUR RECENT COST AND MANPOWER FIGURES, OUR PROJECT MANAGER GIBSON AND I WILL FORWARD THE NTF-BCI PROPOSAL TO EEC-AID HEADQUARTERS IN GENEVA AT OUR EARLIEST OPPORTUNITY.

I LOOK FORWARD TO SEEING YOU IN WASHINGTON THIS WEEKEND.

197663 TRANSCEN

BCI GILO

.....

0825 11/21

PLS REPLY VIA TRT

TABLE 1

BASIC DRILL HOLE STATISTICS

DRILL HOLE	START	COMPLETION	CASING		TOTAL DEPTH		YIELD		STATIC LEVEL	
			FT	METERS	FT	METERS	GLS/MIN	LTRS/SEC	FT	METERS
Borama #1	07/14/86	07/30/86	40'	12.2	138'	40.2	260gpm	16.5	3.1'	1
Borama #2	08/06/86	08/14/86	43'	13.1	134'	40.9	114gpm	7.9	33.4'	10.2
Borama #3	08/21/86	09/08/86	73'	22.3	199'	60.7	200gpm	12.6	46.3'	14.1
Baqi #1	09/27/86	10/07/86	17'	5.2	438'	133.5	--			
Baqi #2	10/15/86	10/16/86	37'	11.2	438'	133.5	200gpm	12.6	108'	32.9
Baqi #3	10/28/86	10/30/86	19'	5.8	449'	136.9	200gpm	12.6	122.5	37.3
Baqi #4	11/03/86	11/19/86*	--		282	86.0	220gpm	13.9	56	17.0

* Date of telex reporting results. Hole was finished after Paul Lapierre's departure.

national water well association
6375 Riverside Dr./Dublin, OH 43017/614-761-1711, Telex 241302
PROVIDING AND PROTECTING GROUND WATER FOR THE WORLD

March 24, 1986

Robert A. Bisson, Chairman
BCI GEONETICS, INC.
Corporate Headquarters
Airport Road P.O. Box 529
Laconia, New Hampshire 03247

Dear Bob:

I really appreciate your comprehensive letter of March 13th and the very excellent reports you included with it. I am very, very impressed with the work you did in Somalia. Your report may not be as fancy as the Dames and Moore-style you referred to, but there is little doubt of the tremendous information you obtained. I was also impressed by the innovative illusion of the color xerox copies of photos.

I have been in the office less than 4 days in the past 2 months, and a trip to New Hampshire in the near future would not be possible. I have to be in Massachusetts on the 1st of June and might be able to work something out on the 2nd of June.

Well before that, however, it may be possible to get together on the Bangladesh situation. I am going to be making a presentation on this subject to top officials at the Bank on May 23rd, and as you will be in the country, I will make an effort to have you included in this day-long, educational program and official reception that evening. Please let me know if you would be interested and available.

Under separate cover, I'm sending you my copy of the "Geology and Groundwater Resources of Bangladesh" report prepared by Paul Jones, formerly of the U.S. Geologic Survey. Please peruse it and return it within two weeks. Any comments will be appreciated.

I think you would be an outstanding firm to work on this project, and I will strongly recommend your services.

Best wishes,

JHL/pcf

Jay H. Lehr, Ph.D.
Executive Director

UNITED NATIONS NATIONS UNIES

POSTAL ADDRESS—ADRESSE POSTALE UNITED NATIONS, N.Y. 10017
CABLE ADDRESS—ADRESSE TELEGRAPHIQUE UNATIONS NEWYORK

REFERENCE:

1 October 1986

Dear Mr. Bisson,

Mr. Maurice Strong has asked me to review the documentation on the Northwest Somalia Ground-water Development programme which you sent to him under cover of your letter of 29 September.

We are familiar, in OEOA, with a good deal of the work being carried out in Northwest Somalia, because of our close association with the refugee/returnee assistance programmes being implemented in that part of the country. Clearly, improved water availability both for human and animal consumption is of key importance throughout the area, both for the refugees and the local population.

→ Unfortunately, OEOA will be disbanded, as a separate office of the United Nations, on 31 October 1986. You can well imagine that under these conditions our capacity to mobilize resources for emergency assistance programmes is virtually non-existent.

As our own financial resources are totally expanded, I have forwarded the material you sent to Mr. Strong to the Regional Bureau for Arab States of UNDP. Their field office in Mogadiscio manages an important programme of technical assistance, and I am certain that they will be interested in the objectives and results of your activities. I would suggest that you contact UNDP directly regarding a possible association in the further implementation of the programme.

Yours sincerely,

Charles-Henri La Munière

Charles-Henri La Munière
Executive Co-ordinator
Office for Emergency Operations in Africa

Mr. Robert A. Bisson
Chairman
BCI Geonetics, Inc.
Airport Road
P.O. Box 529
Laconia, N.H. 03247

APPENDIX III
Drilling Equipment Upgrade Specifications

DROUGHT RELIEF PACKAGE

BASE RIG AND OPTIONS

TH-10 DHD/ROTARY PACKAGE FOR 6" WELLS

TH-10 STANDARD MODULE

Pipe Rack

Night Lights

Dust Curtain

Tool Box

Water Injection

DHD Lubricator

Console Cover

MOUNTED ON 4 X 4 TWO AXLE TRUCK WITH DIESEL ENGINE

MOUNTING INCLUDED AT NO CHARGE

Prices include drill mounting and two (2) week start-up in the field by a factory start-up/training specialist.

Prices include three (3) sets of operation/parts books.

DROUGHT_RELIEF_PACKAGE

PORTABLE_AIR_COMPRESSOR

IH-10

1	600 cfm/150 psi Portable Screw Compressor
1	50' Bull Hose
1	Spare Parts Package

DROUGHT RELIEF PACKAGE

TOOLS AND ACCESSORIES

TH-10 AIR

Drill Pipe:

50 pcs. 4" x 10' x 2-7/8 IF Drill Pipe

Down Hole Drill:

1	DHD-160
6	DHD-160 Bits 6"
2	DHD-160 Bits 8"
1	DHD-160 Sub

Down Hole Accessories:

1	J-Wrench
1	Drill Disassembly Wrench
1	Bushing
1	Bit Detaching Chuck 6"
1	Bit Detaching Chuck 8"
1	Chuck Adapter

Rotary Drilling Accessories:

1	7-1/2" x 8' Stabilizer
1	Stabilizer Bushing
1	Stabilizer Holding Wrench
1	2-7/8 IF Hoist Plug
1	2-7/8 IF Lifting Bail
4	7-7/8" Steel Tooth - Medium - Rotary Bit

Rotary_Drilling_Accessories: (Continued)

1	7-7/8" Steel Tooth - Soft - Rotary Bit
1	Bit Detaching Chuck 7-7/8"
1	Bit Chuck Adapter
1	4-1/2 Reg. Lifting Bail

Miscellaneous_Accessories:

1	Casing Clamps for 6" Casing
1	Drill Pipe Spear
1	Drill Pipe Overshot
1	DHD Overshot
1	Metric Tool Kit and Tool Box
1	36" Chain Wrench
1	48" Chain Wrench
1	10 lb. Sledge Hammer
2	Shovels
2	Hard Hats
6	Pair Work Gloves

Lubricants:

2	35 lb. Thread Lube
2	Drums (55 gal.) Hydraulic Oil
2	Drums (55 gal.) Rock Drill Oil for DHD

Spare_Parts:

1	Year's recommended spare parts package for remote locations

DROUGHT RELIEF PACKAGE

BASE RIG AND OPTIONS

TH-10 MUD ROTARY PACKAGE FOR 6" WELLS

TH-10 MUD MODULE

4 X 5 Duplex Mud Pump

Pipe Rack

Night Lights

Dust Curtain

Tool Box

Console Cover

MOUNTED ON A 4 X 4 TWO AXLE TRUCK WITH DIESEL ENGINE

MOUNTING INCLUDED AT NO CHARGE

Prices include drill mounting and two (2) weeks start-up in the field by a factory start-up/training specialists.

Prices include three (3) sets of operation/parts books.

DROUGHT RELIEF PACKAGE

TOOLS AND ACCESSORIES

TH-10 MUD

Drill Pipe:

50	4" x 10' x 2-7/8 IF Drill Pipe

Rotary Drilling Accessories:

1	7-1/2" x 8' Stabilizer
1	Stabilizer Holding Wrench
1	Stabilizer Bushing
1	9-1/2" x 8' Stabilizer
1	Stabilizer Holding Wrench
1	Stabilizer Bushing
4	7-7/8" Steel Tooth - Medium - Drill Bit
2	7-7/8" Steel Tooth - Soft - Drill Bit
2	9-7/8" Steel Tooth - Medium - Drill Bit
2	9-7/8" Steel Tooth - Soft - Drill Bit
1	7-7/8" Bit Detaching Chuck
1	9-7/8" Bit Detaching Chuck
1	Bit Chuck Adapter
1	2-7/8 IF Hoist Plug
1	4-1/2 Reg. Lifting Bail
1	6-5/8 Reg. Lifting Bail

Miscellaneous Accessories:

1	Drill Pipe Spear
1	Drill Pipe Overshot

[illegible]: (Continued)

1	Metric Tool Kit and Box
1	36" Chain Wrench
1	48" Chain Wrench
1	10 lb. Sledge Hammer
2	Shovels
2	Hard Hats
6	Pair Work Gloves

Lubricants:

2	35 lb. Pails Thread Lube
2	55 gallon Drums Hydraulic Oil

Drilling Fluids:

100	50 lb. Bags Bentonite Drilling Mud
5	20 lb. Cartons Quick Trol
1	Mud Scale
1	Viscosity Funnel and Cup
1	Sand Content Kit
1	Mud Mixing Set

Spare Parts:

1	Year's recommended spare parts for remote locations

TALKING POINTS OUTLINE

- WHAT R.S. CENTER CAN DO
- RELATION TO OFDA/AID PRIORITIES
- WAYS WE COULD COLLABORATE

I. BRIEF HISTORY OF R.S. CENTER:

Objectives
Clients
Services
Donor Participation (including AID)

II. INSTITUTIONAL CAPACITY:

Technical/Professional Skills
Regional Focus
Contacts with 23 E. African Countries

III. POTENTIAL FOR COLLABORATION:

Natural Resources Inventories
Disaster Mitigation/Relief Operations
Regional/Local Environmental Issues
GIS Information/Planning Services
Private Sector Technology Expansion

IV. CURRENT CENTER OBJECTIVES:

Improve Links with the Private Sector
Expand Technology Applications/Projects
U.S. Contacts: Africa & Other Units

POSSIBLE R.S.C. - A.I.D. COLLABORATION

- NATURAL RESOURCES INVENTORIES
- DISASTER MITIGATION PROJECTS
- REFUGEE RELIEF PLANNING
- ENVIRONMENTAL STUDIES
- CROPPING STUDIES
- DISEASE PREVENTION PROGRAMS
- LIVESTOCK/WILDLIFE MANAGEMENT
- WATERSHED ASSESSMENTS
- GIS/TECHNOLOGY APPLICATIONS
- REGIONAL INFRASTRUCTURE STUDIES
- TRAINING-INFORMATION DISSEMINATION

AREAS OF COMMON INTEREST AND POTENTIAL COLLABORATION

REGIONAL/TRANSNATIONAL CONDITION SURVEYS:

Agriculture; Watersheds; Food Production Areas;
Natural Resources; Human/Wildlife Interfaces; etc.

BACKGROUND INFO FOR DISASTER PLANNING/MGMT.

Aerial Photos; Satellite Data; Mapping Services;
Time-Line Changes (Cropping, Population, Infrastructure)

RESOURCES LOCATIONS/OPTIONS:

Food Crops, Water, Benevolent Climates/Terrain s
Relief Support Facilities

DISASTER MGMT. INSTITUTIONAL LINKAGES:

Technology Access, Image Processing, Analysis Services,
Contacts with E. African Ministry Officials, Training Capacity

Drilling equipment and supplies:

An informal survey of suitably-sized and potentially available drilling rigs in Ethiopia was conducted by the BEC team under previous contract. The survey revealed that several rigs presently operate in the country, including American-made Ingersoll Rand T-60's and a T-10, British-made Halco V766, and small Japanese and Italian rigs which could be retrofitted for the project. The rigs are in various states of repair and will require maintenance and refurbishment of some sort or another. The selection of the project drilling rig will be made contingent upon the areas selected for test drilling, rig availability and terrain accessibility.

Given the wide range of mechanical problems affecting individual rigs, certain items and equipment must be ordered only after an on-site inspection of the chosen rig is conducted. The reason for proceeding in this manner is that each rig has certain failings and problem equipment. The on-site evaluation reveals the types of problems and failures which occur for the particular rig to be used on the project and is necessary to avoid excessive down time and/or project failure. For example, the pre-drill phase evaluation and selection of both rig and crew used in a logistically and environmentally similar exploration project in the Northern Ogaden of Somalia lead to the timely construction of wells for the project. Because spare parts and equipment were on-hand during the drilling, the drilling process proceeded smoothly. When parts failed, they were easily replaced, resulting in minimal downtime. If the inspection and rig history had not been completed, the drilling program would have been terminated prematurely while waiting for spare parts to be ordered, constructed and shipped from overseas vendors (a process which takes weeks or months and is extremely expensive).

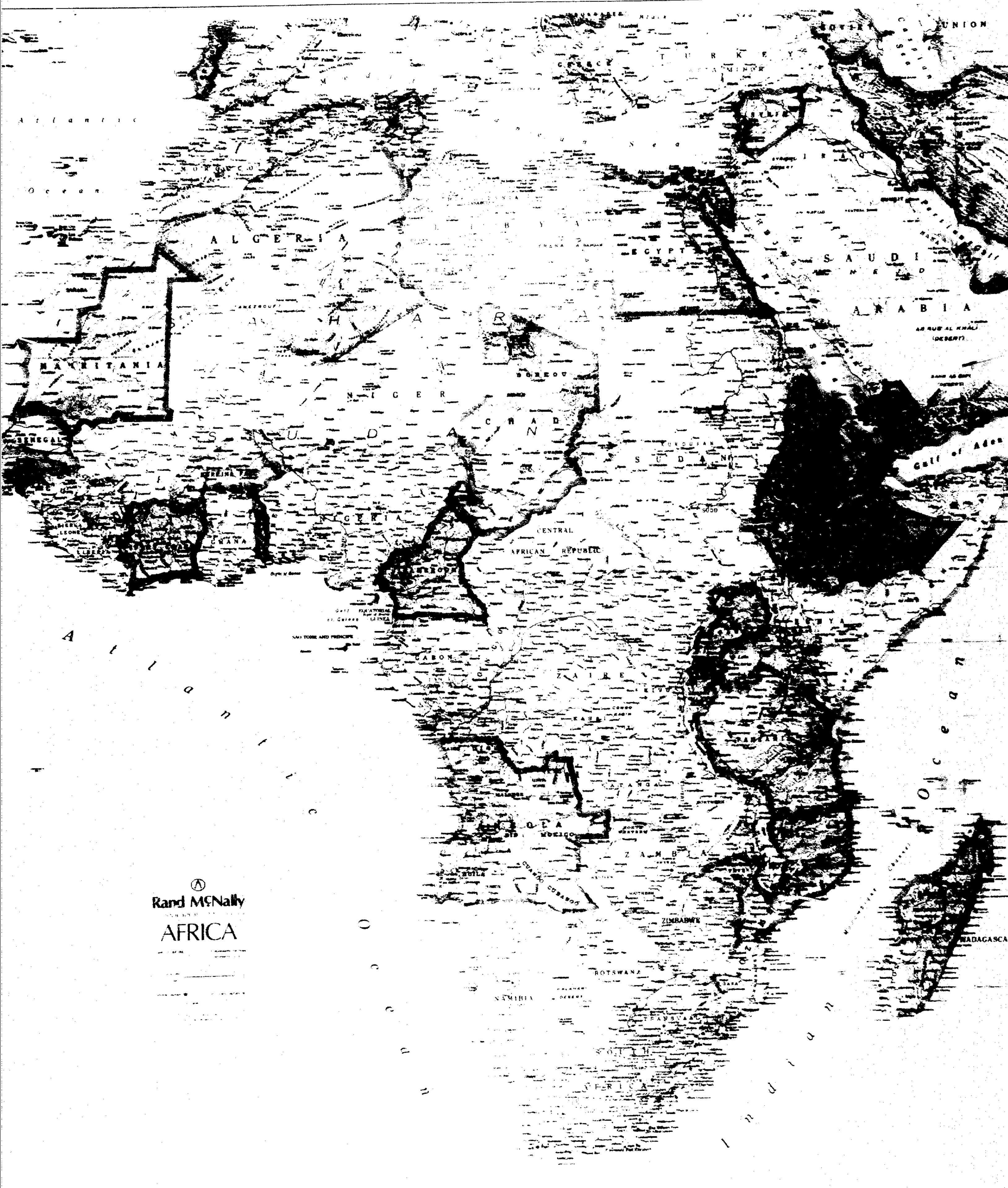
Given that we do not yet know the specific rig which will be used for the project and that an itemized budget must be presented with this proposal, we have made the assumption that an Ingersoll Rand Th-60 would be used for the project.

The following itemized budget for equipment and materials reflects our knowledge of this rig's particular mechanical failings. Should alternative rigs be chosen for the project, we feel that equipment and spare parts costs will be roughly comparable. Transport costs/duties and fees may be different if the goods are acquired from non U.S. suppliers.

The trailer-mounted compressors and mud pumps itemized below will be needed for the construction of deep, large-volume water supply wells. Contingency funds in the amount of $50,000 should be allocated to cover the repair or replacement of additional items discovered as a result of the in-country rig inspection.

JANTITY	DESCRIPTION WELL DRILLING EQUIPMENT		UNIT PRICE		AMOUNT
8	12 1/4" Bits-rerun, Journal, Carbide:	$	1,890.00	$	15,120.00
10	7 7/8" Bits-rerun, AB Med. Form., Carbide:	$	453.60	$	4,536.00
4	8" (Bulldog) Bits for 380 Hammer (Ramblast):	$	1,960.50	$	7,842.00
6	6" Bits (Bulldog) for 360 Hammer (Ramblast):	$	635.00	$	3,810.00
1800'	8" Casing .277 Wall:	$	17.50	$	31,500.00
5	Drilling Foam - 5 Gal. Pails:	$	75.60	$	378.00
100	Drilling Mud - 50 Lb. bags:	$	10.20	$	1,020.00
2	Rock Drilling Oil - 55 gal Drum:	$	302.40	$	604.80
1	9 5/8 Stabilizer 3 1/2 IF Box W/Flats: 4 1/2" across X 5 1/2" OD Neck X 6 5/8 API Box down BBF X 15' X Smooth X 1/2" Wall with check Valve:	$	3,290.00	$	3,290.00
1	6 5/8" Stabilizer 3 1/2 IF Box up X 4 1/2 API Box Down W/IR Flats, BBF, with Check Valve:	$	1,890.00	$	1,890.00
1	6" Ingersoll Patern Hammer:	$	7,408.80	$	7,408.80
1	8" Ingersoll Pattern Hammer:	$	12,806.40	$	12,806.40
600'	6" Casing .250 Wall:	$	9.04	$	5,424.00
12	8" Drive Shoe:	$	171.40	$	2,056.80
3	6" Drive Shoe:	$	94.50	$	283.50
1	Crossover Sub 21" S-S 2 7/8 IF Box W/Flats on 4 1/2" OD X 3 1/2 IF Pine on 5 1/2" OD:	$	427.50	$	427.50
1	Split Bushing for 9 5/8" Stabilizer:	$	360.00	$	360.00
1	Split Bushing for 6 5/8" Stabilizer:	$	390.00	$	390.00
4	Cases of Easy Mud:	$	157.50	$	630.00
1	"J" Wrenceh-for DHD 380 & Stabilizer:	$	262.50	$	262.50
1	Split Table Bushing (TH60) 10 3/4" Opening for 4 1/2" Rod:	$	487.50	$	487.50

2	Foot Valves for 380 (Nylon):	$	36.00 $	72.00
1	Petol Wrench/Chain for DHD380:	$	1,462.50 $	1,462.50
1	B O Basket (TH60) for 8" Hammer Bit:	$	255.00 $	255.00
2	Foot Valves for 360 (Nylon):	$	14.25 $	28.50
2	Compressor Oil - 55 Gal. Drums:	$	1,285.35 $	2,570.70
1	Casing Driver for 8" Case:	$	412.50 $	412.50
1	Set 8" Casing Elevators:	$	2,025.00 $	2,025.00
2	Chain Wrenches:	$	288.00 $	576.00
1	Repair Kit for Mud Pumps:	$	1,520.65 $	1,520.65
2	Sets King Swivel (XV20) Repair Parts W/2 Packing Rings, 1 Wear Bushing, 2 Housing Seals:	$	140.00 $	280.00
2	Hydraulic Oil - 55 Gal. Drums:	$	286.30 $	572.60
1	2.5 Gal Pail - Tread Compound:	$	72.00 $	72.00
1	Grease Gun:	$	22.50 $	22.50
1	10-(Pack) Cartridges for Grease Gun:	$	100.00 $	100.00
1	Gear Oil # 140 Grade - 5 Gal. Pail:	$	44.70 $	44.70
2	Mineral Oil - 5 Gal. Pails:	$	41.50 $	83.00
1	Motor Oil for Cat Eng. - 55 Gal. Drum:	$	307.50 $	307.50
2	5' Screens each with male and female Couplings:	$	808.00 $	1,616.00
1	900 X 350 PSI Ingersoll Rand Trailer Mounted Compressor (2 in Stock-5 days Delivery):	$	121,986.25 $	121,986.25
	or			
1	900 X 350 PSI Sulair Tandam Wheel Mounted (12 Weeks Delivery):	$	110,112.50	
400'	Air Hose With Connections:	$	10.60 $	4,240.00
1	5 X 6 Air Driven Mud Pump With 100' of 4" Rubber Water Suction Hose:	$	11,600.00 $	11,600.00
			Total	$250,375.20



Rand McNally
AFRICA
Atlantic Ocean
TURKEY
GREECE
UNION
ALGERIA
MAURITANIA
SAHARA
NIGER
CHAD
EGYPT
SAUDI
ARABIA
AR RUB' AL KHALI (DESERT)
Gulf of Aden
SUDAN
SENEGAL
GHANA
NIGERIA
CENTRAL AFRICAN REPUBLIC
GABON
SAO TOME AND PRINCIPE
ZAIRE
ZAMBIA
ZIMBABWE
BOTSWANA
NAMIBIA
SOUTH AFRICA
MADAGASCA
Atlantic Ocean
Indian Ocean