The Third Annual
D. R. F. Harleman Honorary Lecture in Environmental Fluid Mechanics

The Great Man-Made River in Libya: Does it Make Sense?

by

Daniel P. Loucks
Department of Civil and Environmental Engineering
Cornell University

November 5, 2004
4:35 pm
102 Thomas Building

The Pennsylvania State University
Department of Civil and Environmental Engineering
College of Engineering
University Park, PA 16802

DONALD R. F. HARLEMAN HONORARY LECTURE IN ENVIRONMENTAL FLUID MECHANICS

The Harleman Lecture serves to honor Dr. Donald R. F. Harleman, a Penn State alumnus who distinguished himself in the fields of hydraulics and environmental engineering as a student and a member of the faculty at the Massachusetts Institute of Technology (MIT) from 1945 through 1991, when he retired as a professor emeritus. He currently holds the title of Senior Lecturer at MIT.

The Lecture was established by an initial grant in November of 2001 from Joseph R. Reed, Professor Emeritus of Civil Engineering at Penn State. It was formally approved in February 2002 by the University's Board of Trustees as the "Donald R. F. Harleman Endowment in Environmental Fluid Mechanics". The endowment will be supplemented in the future through an estate plan bequest made by Dr. Harleman in July 2002.

The Harleman Lecture is intended not only to enrich the faculty and students in the hydrosystems division of Penn State's Civil and Environmental Engineering Department, but also any interested student, faculty, or practicing engineer as well, by providing contact with outstanding researchers and practitioners in the field from outside the University. The lecture will be a fall semester parallel to the very successful Kavanagh Lecture in Structural Engineering established in 1994 and held annually in the spring.

PREVIOUS HARLEMAN LECTURERS

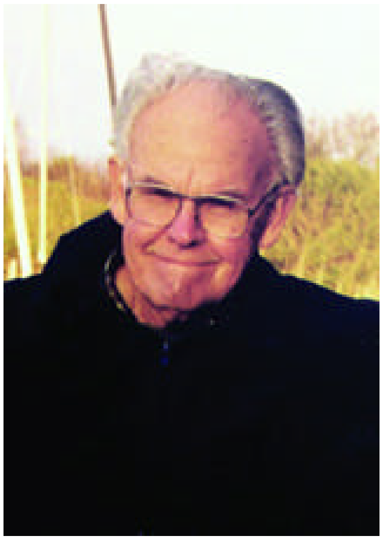
2002……………………………………….………………….. Donald Harleman

2003……………………………………………………William Bingham

PROGRAM

Reception	
Opening Remarks	*Dr. Christopher Duffy Professor of Civil Engineering The Pennsylvania State University*
Welcome	*Dr. Andrew Scanlon Professor and Head Civil & Environmental Engineering The Pennsylvania State University*
Introduction of Speaker	*Dr. Christopher Duffy Professor of Civil Engineering The Pennsylvania State University*
Harleman Honorary Lecture	*Dr. Daniel P. Loucks Professor of Civil Engineering Cornell University*
Questions and Answers	*Drs. Duffy and Loucks*
Presentation	*Dr. Reed Professor Emeritus of Civil Engineering*
Closing Remarks	*Dr. Duffy*

Donald R. F. Harleman



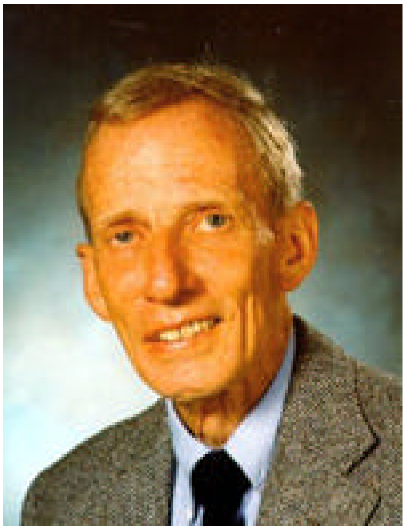
Donald R. F. Harleman, a native of Palmerton, PA, received his B.S. C.E. degree from Penn State in 1943 and his M.S. and Sc.D. degrees in Civil Engineering in 1947 and 1950 from the Massachusetts Institute of Technology (MIT). He worked as a design engineer for Curtis-Wright Corporation in Ohio during WWII. Through 1962 he held research and faculty positions in Hydraulics at MIT, and in 1963 he became Professor of Civil Engineering. He was appointed Ford Professor of Environmental Engineering in 1975, and achieved Emeritus status in 1991. He currently holds the title of Senior Lecturer at MIT.

Dr. Harleman has been an active member of the National Academy of Engineering and is an Honorary Member of the American Society of Civil Engineers (ASCE). He has won six (6) ASCE awards, including two (2) Hilgard Hydraulic Prizes in 1971 and 1973, and a Stevens Award in 1973. The Boston Society of Civil Engineers has honored him with three (3) awards with the latest being in 1990, and he has received two (2) awards from the College of Engineering at Penn State as Outstanding Alumnus in 1979 and as an Alumni Fellow in 1987. He has served as a member of the Board of Editors of the International Journal of Hydraulic Research, and was a member and Chairman of the Executive Committee of the Hydraulics Division of ASCE in the 1960's. He has spent residence time overseas as a visiting engineer at the Delft Hydraulics Laboratory in the Netherlands and at the International Institute for Applied Systems Analysis in Austria, as well as being a Guggenheim Fellow in the Department of Applied Mathematics and Theoretical Physics at the University of Cambridge, England. He gave the First Hunter Rouse Hydraulic Engineering Lecture for ASCE in 1980.

For ten (10) years beginning in 1973, Don Harleman was the Director of the Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics. During that same period, he was the Head of the Water Resources and Environmental Engineering Division of MIT's Department of Civil Engineering. He has a very extensive record of research, publications, and consulting on a national and international level. His current consulting takes him occasionally to Mexico, Hong Kong, Italy, and Brazil.

Don Harleman is a co-holder of two U.S. patents in Hydraulics and environmental engineering. He is the co-author of the 1968 textbook <u>Fluid Dynamics</u>. The Donald and Martha Harleman Professorship at MIT was established in 2000 through an endowment raised by his friends and former students.

Daniel P. Loucks



Professor Loucks teaches and carries out research in systems analysis and environmental management for air, land, and water resources. He has served as a consultant to private and government agencies and various organizations of the United Nations, the World Bank, and NATO involved in regional water resources development planning in Asia, Australia, Eastern and Western Europe, the Middle East, Africa, and Latin America.

Professor Loucks was awarded the Huber Research Prize in 1970 and the Julian Hinds Award in 1986 by the American Society of Civil Engineers. He was elected Fellow in the Society in 1983 and Honorary member in 1998. He was elected to the National Academy of Engineering in 1989. He received Distinguished Lecture Awards by the National Research Council of Taiwan in 1990 and 1999, an EDUCOM Award for software development in 1991, the Senior U.S. Scientist Research Award from the German Alexander von Humboldt Foundation in 1992, and the Warren A. Hall Medal from the Universities Council on Water Resources in 2000. Loucks was commissioned in the U.S. Navy in 1955. He served as an aviator on active duty until 1959 and subsequently in the Naval Reserve until 1981. From 1979 to 1981 he commanded VR-52, the largest Naval Air Transport Squadron in the country having detachments at Naval Air Facility, Detroit, MI, Andrews Air Force Base, MD, and Naval Air Station, Willow Grove, PA. In 1981 he was awarded the Navy’s Commendation Medal by the Secretary of the Navy. He retired as Captain from the Naval Reserve in 1992.

THE GREAT MAN-MADE RIVER IN LIBYA: DOES IT MAKE SENSE?

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ABSTRACT

In the 1950s and 1960s the search for new oilfields in the deserts of southern Libya led to the discovery not only of significant oil reserves, but also of aquifers containing vast quantities of fresh groundwater. Most of this ‘fossil’ water was collected over 35,000 years ago. The demand for fresh water in the mostly desert country of Libya to sustain its economy, especially its agriculture sector, exceeds its traditional supplies. Hence soon after this discovery of fresh groundwater reserves a plan was conceived to pump and transport water from these aquifers in the desert to Libya’s Mediterranean coast where most of its 4 million people live and where the water can be used. This project is called the Great Man-made River. The construction of this ‘river’ of pipes, pumps and reservoirs began in the mid 1980s and continues today. When completed it is expected to cost 25 billion US dollars. In the mid 1990s I had the opportunity to visit Libya and conduct a cost effectiveness and component sequencing analysis of the project for the Great Man-made River Authority. This talk will review and illustrate the incredible engineering challenges being addressed in this project, and the results of our analyses. I’ll also discuss some issues of sustainability relevant to the depletion of non-renewable resources, such as Libya’s groundwater reserves.

WATER FROM THE DESERT: MINIMIZING COSTS OF MEETING LIBYA'S WATER DEMANDS

A. M. El-Geriani, O.Essamin, D. P. Loucks

Libya has two choices for meeting its water demands: the Mediterranean Sea and groundwater from the Sahara Desert. We performed two studies supporting Libya's decisions regarding further investments in desalination and in groundwater pumping and conveyance systems. We used static and dynamic mixed-integer optimization models to identify least-cost combinations of investments in infrastructure that would meet specified water demands at specified sites. Desalination does not appear to be an economically efficient alternative to the groundwater system, called the "Great Man-made River Project" (GMRP). Results from the static models showed that as water demands increase, various new GMRP components are needed, then get replaced by other new units, and then, under higher demands, are needed again. This demonstrated the need for dynamic capacity-expansion-planning models. The results of both studies are contributing to the Great Man-made River Authority's decision making.

Libya, bordering the Mediterranean Sea in Northern Africa, is mostly desert. But under much of that desert sand is a large amount of water and energy. The groundwater resulted from hydrological events that happened many thousands of years ago. Today Libya is exploiting (or mining) this water for the benefits of its people. To enable the people of Libya to use the water where most of them live—along the Mediterranean coast—Libya has planned, designed, and implemented the world's largest and most expensive groundwater pumping and conveyance project. It is called the Great Man-made River Project (GMRP) [Mayne 1993; Salem 1991, 1992]. Construction began in the mid-1980s and still continues. Our studies identified least-cost development strategies for expanding the GMRP and for desalination plants along Libya's Mediterranean coast.

The Great Man-made River Project

It has been known for some time that groundwater exists under the sand of the Sahara Desert. Explorations for oil in the Sahara Desert. Explorations for oil in the Sahara Desert of Libya during the 1960s further defined the extent of these groundwater aquifers. The water in these aquifers is ancient, thought to be derived from precipitation and percolation that occurred some 15 to 40 thousand years ago. The volume of this "fossil" water is estimated to exceed 35,000 cubic kilometers. Without foreign or international financial support (but rather with funds obtained from taxes on gasoline, tobacco, and travel), Libya began to design and install the hydraulic infrastructure needed to withdraw and transport this groundwater some 800 kilometers from its sources to various demand sites along its Mediterranean coast (Figure 1). Phase 1 in the east, with the exception of the Tazerbo well field, and Phase 2 in the west are now in operation (but not at their design capacities). The western system delivered its first water to Tripoli on September 1, 1996. (As expected, the old water distribution system within Tripoli broke under the pressure and flooding resulted!) Phase 3, yet to be developed, would allow transfers of water between the western and eastern systems (in either direction), would develop the Kufra well field, and would extend the eastern system eastward to serve a number of communities including Tobruk.

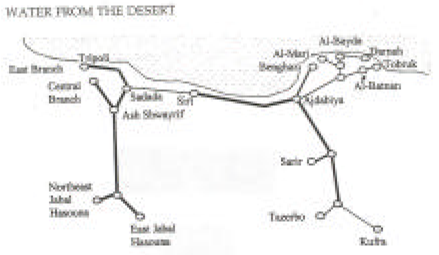

Figure 1: In this map of Libya's Great Man-made River Project, the darker (thicker) lines represent existing conveyance pipelines. Phase 1 of the GMRP is the existing eastern (right-hand) system plus the Tazerbo well field. Phase 2 is the existing western (left-hand) system. Phase 3 is the remaining system not yet installed. Current production is less than maximum planned capacity. The maximum planned capacity exceeds 2.5 million cubic meters per day from the western well fields and 3.6 million cubic meters per day from the eastern well fields.

If one were to overlay Libya on top of Western Europe, the portion of the Great Man-made River from Kufra to Tripoli would extend from southern Switzerland to Northern Scotland.

To appreciate further the scale of this engineering project, consider the following: The critical-path-method (CPM) network used in coordinating and managing the construction activities included over 36,000 separate tasks. Just the existing eastern portion (the first of three phases) of this project required manufacturing and installing approximately 250,000 7.5-meter-long, four-meter-diameter prestressed-steel-and-concrete pipe sections each weighing some 86 tons. This was done in an environment where sand can be blowing around at temperatures in excess of 50 C° (122 F°). The project required the "largest concentration of earth-moving and handling equipment in the history of civil engineering" [GMRA 1989, p. 14].

Separate well fields and conveyance pipes (not shown in Figure 1) had to be developed and installed just to provide water for the pipe-manufacturing plant. Roads had to be built into the desert, with roadbed material transported from the coast. Maintaining these roads and the hundreds of installed wells requires the sometimes daily removal of blown sand. Old rubber tires are used to mark the location of roads that might otherwise be obscured by sand. Power plants had to be constructed and high voltage power lines installed. Hundreds of kilometers of high-voltage lines deliver electric energy to the pumps in the southern well fields. The coating of sand that builds up on these lines has to be washed off with water every six months or so. Five camps (called operation, support, and maintenance centers) located along the pipeline had to be built. These camps provide housing, food, entertainment, and other needs to the people responsible for maintaining and operating the pumps, pipes, and power facilities. Open holding reservoirs and enclosed header tanks had to be built to provide for variations in supplies and demands. While most of the water flow in the conveyance system is by gravity, some pumps along the pipelines will be needed to meet the projected higher demands. Pressures within the conveyance pipes may reach 20 atmospheres. Treatment facilities are required to reduce water salinity and buildup of chemical deposits along the pipes. Holding reservoirs require periodic draining and cleaning—including the removal of fish that people put in them. Elaborate control and communication systems for system day-to-day management were developed and installed. They must now be maintained and operated. (Currently GMRA is developing real-time optimization models to guide those responsible for day-to-day operation.) Air-conditioned trucks and buses continue to be needed for transport of material and personnel.

In a front-page article of a newspaper that claims to print "all the news that's fit to print," Bonner [1997] suggests that Libya may be building the GMRP for transporting and storing military material and personnel. Quite a feat for the hydraulic design engineers engaged in this project. Observers of the GMRP can reach a more informed opinion.

The design, development, and implementation of the GMRP was, and continues to be, under the direction of the London, UK, branch of Brown and Root Consulting Engineers, Ltd. The main construction contractor is Dong Ah Consortium of South Korea. In 1983, the Great Man-made River Management and Implementation Authority (GMRA) was established for planning, overseeing, and approving each subproject as well as for operating the system. Its headquarters and main control center is in Benghazi. These organizations provided the GMRP data we used in our cost-effectiveness studies. We obtained data on the cost of desalination from the studies of Alain [1996] and Bushnak [1996a, 1996b].

Study Objectives

We undertook these cost-effectiveness studies under the direction of the United Nations Educational, Scientific, and Cultural Organization (UNESCO) at the request of the GMRA. Their purpose was to identify minimum-cost combinations of GMRP components and desalination to meet the future water demands of Libya. We took into account the operation, maintenance, and repair (OMR) costs of all existing GMRP components and the manufacture, installation, and OMR costs of all the additional components being considered for expanding and extending the system. In addition, the study included the costs of building and operating desalination plants along the coast. We were asked not to consider other sources of water or to perform any benefit, risk, or environmental-impact analyses.

To conduct the cost-effectiveness studies, we needed to identify

—All well-field characteristics relevant to the supply and quality of groundwater, the expected drawdown rates, and the depths of groundwater heads that affect the costs of pumping over time at each existing and potential well field;
—All water demand sites and the ranges of future water demands being considered at each of these sites;
—Alternative options for providing water from the GMRP and from desalination plants to meet the demands at each demand site;
—Future annual capital and operation, maintenance, and repair costs of each of the components of the alternative systems, taking into account the economic lives of the system components; and
—Least-cost combinations and capacity-expansion schedules of the GMRP and desalination components required to meet the estimated ranges of possible future demands at all demand sites at minimum costs, and the impact of parameter uncertainty in system design, operation, and cost.

Analysis Procedures and Assumptions

We focused our analyses on the various phases of the GMRP (Figure 1). Phase 1 is the eastern (right-hand) portion and Phase 2 is the western (left-hand) portion. Phase 3, yet to be constructed, includes the Kufra well field, the extension from Ajdabiya eastward to various cities including Tobruk, and the extension linking Sirt and Sadada that will enable the transfer of water between the eastern and western phases. Once that extension connecting the eastern and western systems is completed, water can flow between Ajdabiya and Sadada in either direction (but at different costs). We combined these separate components of the overall GMRP in various ways to estimate the costs of alternative system configurations for transferring water among the portions of the entire system. We compared these costs to the costs of producing and providing desalinated sea water to coastal demand sites, where feasible, and to the costs of using various combinations of GMRP water and desalinated sea water.

To obtain least-cost estimates of meeting prespecified demands for water, we developed static (single-period) mixed-integer optimization models for each of the GMRP/desalination configuration scenarios (appendix). Each model described the physical system being analyzed in enough detail for estimating the minimum annual costs of meeting the demands for water. In addition to these annual costs, we identified the infrastructure (wells, pipes, pumps, and desalination-plant capacities) and flows throughout the system required to meet the prespecified demands at minimum annual costs.

Based on the results of these static analyses, we developed four dynamic optimization models to identify least-cost capacity expansion schedules for the GMRP (appendix). These models were for the eastern subsystem, the western subsystem, the portion of the GMRP connecting the eastern and western subsystems, and the Tobruk extension to the eastern subsystem.

By solving the models we obtained the changing values over time for
—The flows within and the capacities of each of the components throughout the GMRP;
—The number of wells needed in each well field, including the reserve requirements; and
—The capacities of the desalination plants at coastal demand sites.

We constrained the values of the GMRP variables to be within their known upper limits, if applicable. The values of the unknown design and operating variables obtained from the model solutions are those that will meet the specified demands for water at minimum costs. All costs, fixed and variable, are functions of these unknown system-design and operating variables.

In each model, the known parameters included, as applicable,
—The configuration and capacities of existing pipes and pumps;
—The locations and maximum capacities of any additional (new) pipes and pumps;
—The water losses due to evaporation from reservoirs;
—The locations of demand sites and the demands for water over time at each site;
—The installation and OMR costs of all future conveyance pipes and pumps, well fields, and desalination plants;
—The interest rates used to convert one-time (initial) fixed costs to annual costs; and
—The recovery periods (economic lives) of wells, pipes, pumps, and desalination plants.

Manufacturing, installation costs, and OMR costs have both fixed and variable components. Fixed costs are independent of the design flow or of the variables used to determine the design flow (such as pipe diameters or number of wells operating and in reserve). Variable costs depend on the flow. We converted all fixed (one-time) costs of developing new well fields, pipes, and pumps to annual costs assuming a three- to six-percent annual compound-interest rate, a well and pipe life of 30 to 50 years, and a pump life of 15 years. We performed sensitivity analyses on these economic parameters to show how sensitive the total annual cost estimates are to these assumed values. We added the annualized fixed installation costs to the annual fixed and variable OMR costs to obtain total annual costs as a function of the required flow.

In some of our analyses, we considered salinity quality constraints that required mixing waters from different well fields; for example, Sarir, Tazerbo, and Kufra all have different salinity concentrations. In other analyses, we assumed flow could go in either direction along the Ajdabiya to Sadada portion of the GMRP. We assumed that flow in an easterly direction will require pumping, whereas gravity would provide flow in a westerly direction up to a certain threshold. Over that threshold, pumping will be required.

Results of Static Analyses

In the static analyses, we generated and compared over 250 separate scenarios or model solutions. Each model solution represented a particular demand-and-system configuration scenario. Each scenario group included a number of design flows, ranging from no demand (zero flow) to the maximum demand that usually corresponded to the maximum flow for that system. We show some of the results of these scenarios, plotted on graphs showing the annual costs and costs per cubic meter of meeting any particular flow requirements at one or more specified sites, to illustrate some of our interesting findings.

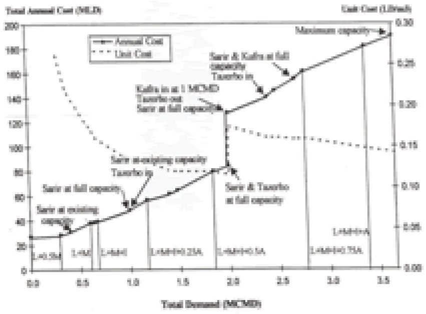

Figure 2: In this graph of minimum total annual costs and per-cubic-meter costs of providing groundwater from the eastern (Sarir, Tazerbo, and Kufra) well fields to meet various municipal (M), industrial (I), and agricultural (A) demands and to account for the expected losses (L), annual costs are expressed in millions of Libyan dinars (MLD) and demands are expressed in millions of cubic meters per day (MCMD). Points on the graph are identified where well-field capacities and combinations change or where maximum capacities are reached.

First, consider only the entire eastern system extended to Sadada in the west. In this set of scenarios the Sarir, Tazerbo, and Kufra well fields are potential sources of groundwater. As the total demand for water increases at all demand sites downstream of Ajdabiya from zero to 3.68 million cubic meters per day (MCMD), the minimum total annual cost ranges from eight to 180 million Libyan dinars (MLD) per year. The cost per cubic meter ranges from about 0.22 to 0.13 LD (Figure 2). We compared these costs to those of desalination. Assuming an optimistic estimate of desalination cost of US$ 0.90 per cubic meter and using the official, rather than the international, exchange rate of about US$ 2.80 per LD, desalinated water would cost about 0.32 LD per cubic meter. Alternatively, using an international exchange rate of about 0.32 US$ per LD, the cost would be about 2,80 LD per cubic meter. Both estimates are higher than the estimated costs of supplying water from the GMRP. More detailed analyses, for example, to compare the added cost of meeting Tobruk’s demand from the GMRP and from desalination, generally lead to the same conclusion except over limited ranges of total demand where GMRP fixed costs of capacity expansion are required. Given the infrastructure already in place, water from the GMRP is generally less expensive than water from desalination.

Figure 3 shows the minimum-cost combinations of eastern well field production required to meet various total demands. Based on the data we used in our analyses, demands up to 1.0 million cubic meters per day (MCMD) can be met most economically by the existing Sarir well field. Demands from 1.0 to 1.4 MCMD can be met most economically by producing 0.4 MCMD at the Sarir well field and 0.6 to 1.0 MCMD at the Tazerbo well field. Demands from 1.4 to 2.0 MCMD are most economically met by full production of 1.0 MCMD at tazerbo and 0.4 to 1.0 MCMD at the Sarir well field. Demands from 2.0 to 2.68 MCMD can be met most economically by full production of 1.0 MCMD at Sarir, of 1.0 to 1.68 MCMD at Kufra, and none at the Tazerbo well field. Demands from 2.68 to 3.68 can be met most economically by full capacity production of 1.0 MCMD at the Sarir and Tazerbo well fields and by producing the remaining 0.68 to 1.68 at Kufra.

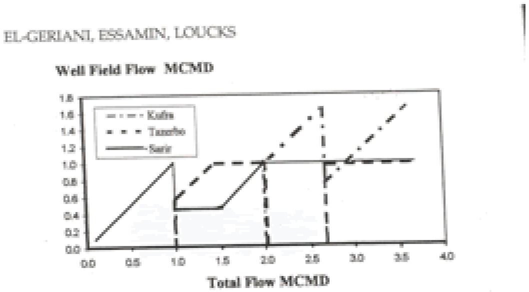

Figure 3: The minimum-cost combinations of eastern well-field flows to meet various water demands shown here is not a capacity expansion plan but merely the flows required to meet specific fixed demands. Adding capacity will change the minimum-cost well-field-production flows required to meet additional demands.

Once the capacity of the Sarir well field is reached, the next most economical alternative is to construct the Tazerbo well field. Once the fixed costs of the Tazerbo well field are paid, it becomes cheaper to produce water at Tazerbo than at Sarir beyond Sarir's existing capacity. Even though Tazerbo's fixed costs are greater than Sarir, the variable costs at Tazerbo are smaller than those at Sarir. Kufra does not begin production until the other two well fields are at their maximum capacity, but once Kufra has to be brought into operation, that is, once Kufra's fixed costs are paid, it is less expensive to produce water at Kufra than at Tazerbo. Hence for demands in excess of the maximum capacities of the Sarir and Tazerbo well fields, it is cheaper to use Sarir and Kufra and avoid the fixed costs of Tazerbo. Only when Kufra and Sarir can no longer meet the water demand does Tazerbo come back into production. Since Tazerbo's variable annual installation and operating costs are less expensive than Kufra's if both Tazerbo and Kufra are required, Tazerbo will be at its maximum capacity before additional water is pumped at Kufra. Figure 3 shows the least-cost capacities of each of the three eastern well fields as a function of water demand.

The reduction of pumping in some of the well fields as expected demands increase is the direct result of differing fixed installation costs and variable operating costs. In practice, one would not likely to dose existing well fields to build new ones. Doing that would not recover their fixed installation costs. The existence of already-installed well-field capacities will change the least-cost solutions of further expansion. Hence when planning appropriate development (capacity expansion) schedules, Libya's GMRA should not simply minimize the costs of meeting immediate demands. Rather it should minimize the costs of meeting the immediate demands together with the expected demands on into the future.

Results of the Dynamic Analyses

Using the results from the static studies that showed desalination is not cost-effective, we performed a second set of studies in which we developed and used four dynamic least-cost capacity-expansion models. These analyses identified the timing and extent of construction activities that GMRA should undertake to meet future estimated demand targets at minimum present value costs given possible budget (capital investment) constraints.

In each of the four models, we assumed five consecutive five-year construction periods with increasing demands to be met. We considered various interest rates, including an interest rate of zero, an assumption often made in economic analyses carried out in Libya. With an interest rate of zero, it clearly doesn't matter when capacity is installed, as long as it is available when needed. For interest rates greater than zero, capacity expansion decisions span the 25-year planning horizon, depending on the demand scenarios.

Because of the relatively high fixed installation costs, the solutions of these models usually indicated component additions at their maximum capacities.

The results from the scenarios of each of the four models consistently suggest that to obtain the least-cost capacity expansion of the GMRP, the GMRA should build the Tazerbo and Sarir well fields at full capacity before beginning construction of the Kufra well field. It should also build the Northeast Jabal Hasouna well field to full capacity before the East Jabal Hasouna well field. It should implement the pipeline connecting the eastern and western subsystems when the demand in the west exceeds the capacity of the western well fields, allowing for flow from the eastern well fields to meet the demands of the western portion of the country.

It should build the components of the Tobruk extension to their full capacities in time to meet demands at each of the demand sites in that region of Libya.

The results of these analyses were not influenced by any budget constraints, reliability considerations, or other noneconomic factors. In reality, they may well be. The GMRA is using these models and may add these additional features when and as appropriate.

These capacity expansion models were intended to indicate what decisions to make in the immediate five-year period, not for periods after that. The model solutions for the four future five-year periods should be ignored. At the end of this immediate period, however long it actually is, the GMRA should update the model input data and run the models again to determine the next step in the capacity expansion schedule.

We performed a number of sensitivity analyses to estimate the increase in total annual costs and in per-cubic-meter costs associated with increases in pumping heads at each well field, in interest rates, in energy costs, and in other fixed and variable investment and operating costs, and with the decreases in pipe lives. Changing these parameter values by 10 to 20 percent, and some by over 400 percent, increased the total annual and per meter costs from about zero to 30 percent. These changes in parameter values have little if any impact on the minimum-cost flows or design capacities throughout the system.

Conclusions

Based on the data available for this study and on the assumptions made during these least-cost analyses, it appears that under optimistic estimates of desalination cost and LD/US$ exchange rates, desalination is not a competing alternative to installing new GMRP capacity. Most of the system-configuration and demand scenarios we examined resulted in GMRP costs ranging from about 0.30 to 0.05 LD per cubic meter, depending on the total amount of water delivered to the various demand sites. In general, the production of a cubic meter of desalinated water remains more expensive than the savings resulting from a reduction of one cubic meter of GMRP groundwater. Assuming our data and analyses are correct, arguments for desalination as a means of enhancing security or reliability are much stronger than arguments based on economics.

Considering system reliability and vulnerability, failure of any aquifer for any reason will not happen in one day; it will take years before the salinity of the groundwater becomes unacceptable or before the drop in water level endangers the lifetime of the wells. The major risk is concentrated in the conveyance system. The conveyance system is more vulnerable than the wells and the aquifers themselves. A possible solution to help secure the water supply of the Tripoli area (Jefara Plain) may be to recharge the coastal aquifer with the excess water produced during periods of low consumption. This solution does not apply for Benghazi since it is located over a karstic aquifer that cannot store a large amount of water.

The GMRA has accepted the results of these studies and is basing current decisions on them. It also uses these optimization models under different assumptions regarding the uncertain future costs and demands. Furthermore, these studies have motivated the GMRA to develop real-time operation models to guide the day-to-day operation of the GMRP as system components require maintenance, as water tables lower, as salinity conditions change, and as demands and energy costs change. These models are expected to be interactive, facilitating their use by operators of the system. They are being developed by personnel from the GMRA, with assistance from others, and should be completed by the end of 1998. For a low cost, these studies, as limited as they are, have had an impact on the development of Libya's national water supply and distribution system. In the near future the extension of these studies should have an impact on its operation as well.

Acknowledgements

Our thanks to all those at UNESCO, its advisory board for this project, Philippe Pallas, and to those in the GMRA and Brown and Root, Ltd., in Libya who helped the third author of this paper appreciate the complexity of this project and who provided us with the information we used in this study. We are also indebted to J. Archibald, D. Austin, J.S. Garlock, P. J. Gijsbers, J. C. Lee, L.-Y. Lee, A. Milman, and L. Teeters, all attending Cornell University, who carried out many of the analyses discussed in this paper.

APPENDIX: Cost Minimization Models

We developed mixed-integer cost-minimization models for numerous GMRP/desalination configuration scenarios. Each model had two parts, a total annual cost function that was to be minimized, and a set of economic and physical constraints. Included in the constraints of the models were the water-supply-demand targets to be met. These demand targets forced flows from existing and potential water sources through the conveyance system to the demand sites.

In this appendix, we give the general structure of the node-link models we developed for various system configuration and operating scenarios. All costs are expressed in the 1996 Libyan dinars and are a function of he unknown design flows and capacities. At well-field sites, the costs could be (and, in the actual models, were) expressed as a function of the number of wells. The unknown variables are written in upper case letters. Capacity loss in the dynamic model applies to certain components, for example, well-field pumps, and is a function of their time in operation.

The specific models developed for each analysis scenario included additional constraints, such as for salinity control and for defining separable nonlinear, discontinuous cost functions. Loucks and Pallas [1997] and Milman et al. [1998] give detailed descriptions of these models together with their input data files.

The Static Cost-Minimization Model

minimize TOTAL_ANNUAL_COST
subject to the following constraints:
Cost Definition:

TOTAL_ANNUAL_COST
= S? Annual_Cost? (GMRP_FLOW?)
+ S$_?$Annual_Cost$_?$(GMRP_FLOW$_?$,
DESALINATION_FLOW$_?$).

The sum is over all nodes ?and links ?. Each annual cost includes the fixed and variable portions of the cost functions for the particular node or link. Demand node costs include desalination costs, as applicable. Node and link costs include conveyance pipe pumping, as applicable.

Demand Requirement at Demand Nodes ?:

TOTAL_FLOW$_?$ = GMRP_FLOW$_?$
+ DESALINATION_FLOW$_?$
= Demand_Flow$_?$.

Mass-Balance Requirements at Each Node ?:

S$_{?}$ TOTAL_FLOW$_{?}$ = TOTAL_FLOW$_{?}$.

The sum is over all links ? “flowing into” node ?.

TOTAL_FLOW$_{?}$ — Demand_Flow$_{?}$
— Flow_Loss$_{?}$= S$_{?}$ TOTAL_FLOW$_{?}$.

The sum is over all links ? whose inflow node is ?.

Maximum Capacity Constraints for GMRP Design Flows at Each Node ?and Link ?:

TOTAL_FLOW$_{?}$
= Maximum_Flow_Capacity$_{?}$,

TOTAL_FLOW$_{?}$
= Maximum_Flow_Capacity$_{?}$.

Well Field Production at Each Well Field Node ?:

GMRP_FLOW$_{?}$
= NUMBER_WELLS$_{?}$
(Well_Production$_{?}$) / (1 + Reserve_frac.).

The Dynamic Capacity-Expansion Cost-Minimization Model

minimize S$_{t}$
TOTAL_PRESENT_VALUE_COST$_{t}$
subject to the following constraints:
Cost Definition:

TOTAL_PRESENT_VALUE_COST$_{t}$
= (S$_{?}$ Cost$_{?}$ (ADDITIONAL_CAPACITY$_{?t}$)
+ S$_{?}$ Cost$_{?}$(ADDITIONAL_CAPACITY$_{?t}$))
Discount_factor$_{t}$.

The sum is over all nodes ? and links ?. Each cost includes the fixed and variable portions of the installation and OMR cost functions for the particular node or link. Node and link costs include conveyance pipe pumping capacities, as applicable.

Demand Capacity Requirement at Demand Nodes ? for Each Period *t*:

TOTAL_CAPACITY$_{?t}$
= GMRP_FLOW$_{?t}$ = Demand_Flow$_{?t}$

Demand Capacity Requirement at All Links for ? for Each Period *t*:

TOTAL_CAPACITY$_{?t}$ = GMRP_FLOW$_{?t}$

Continuity of Capacity at Each Node ? and Link ? in Each Period t:

TOTAL_CAPACITY *t+1*
= TOTAL CAPACITY$_{t}$
- CAPACITY_LOSS$_{t}$
+ADDITIONAL_CAPACITY$_{t}$

Mass-Balance Requirements at Each Node ?:

$S_{?}\ \mathrm{GMRP\_FLOW}_{?} = \mathrm{GMRP\_FLOW}_{?}$
for all links ? “flowing into” node ?.

$\mathrm{GMRP\_FLOW}_{?} — \mathrm{Demand\_Flow}_{?}$
$— \mathrm{Flow\_Loss}_{?} = S_{?}\ \mathrm{DESIGN\_FLOW}_{?}$

for all links ? whose inflow node is ?
Maximum Capacity Constraints at Each Node ?and Link ?:

$\mathrm{TOTAL\_CAPACITY}_{t}$
$= \mathrm{Maximum\_Flow\_Capacity}$

Well Field Production at Each Well Field Node ?:

$\mathrm{GMRP\_FLOW}_{?,t}$
$= \mathrm{NUMBER\_WELLS}_{?,t}\ (\mathrm{Well\_Production}_{?}) /$
$(1 + \mathrm{Reserve\_frac.})$.

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Ali M. El-Gheriani, General Manager for Operations, Great Man-made River Authority, Benghazi, Libya, writes: “This is to certify that the results and methods reported in the paper ‘Water from the Desert: Minimizing Costs of Meeting Libya’s Water Demands,’ have been the subject of a workshop in Benghazi and are being used along with the results of a number of other studies by the Great Man-made River Authority in its planning of future extensions. In addition, future analyses will be using the data and model of the study to identify cost-effective capacity expansion policies.”

Contributors

A.M. El-Geriani is general manager of operations, Great Man-made River Authority in Benghazi, Libya. He has had a number of high positions in the Libyan government, including serving as the Libyan ambassador to Germany.

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D. P. Loucks teaches and conducts research in environmental systems engineering at the School of Civil Engineering at Cornell University. While conducting workshops in Benghazi, Libya, on the use of models developed for the Great Man-made River Authority, he was honored to be designated a visiting member of the Benghazi Squash Club. However, he was no match for the better players of that club.

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