Using ArcGIS to Evaluate the Qattara Depression Solar-Hydroelectric Power Project

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Brief Description: In this assignment, students use ArcGIS to evaluate a proposal to generate hydroelectric power by piping water from the Mediterranean and dropping it into the sub-sea level Qattara Depression, allowing evaporation from the effluent lake to balance the inflow.

Context: This exercise is part of an introductory geology course called Geology and Human Events in Africa and the Middle East. The course focuses on the underlying influence of geology and geologic processes on human events.

Prerequisite skills: Students must have basic ArcGIS skills and be able to work with DEMs in ArcMap, create and manipulate hillshades, manipulate layers in ArcGIS, work with attribute tables, calculate areas and volumes, and create map layouts.

Where situated in the course: This exercise takes place as a final project in the course.

Concept goals: Students will consolidate concepts related to hydroelectric power generation, desert hydrogeology, hydropolicy, bedrock geology, and the role that hydrogeology of the Qattara Depression played in World War II.

Higher order thinking skills goals: Students will determine how to do the analyses and do independent evaluation of their data.

Other skills goals: Students will practice GIS skills learned in previous assignments.

Description: Several times over the past 80 years, the Egyptians have considered developing a power generating station tens of meters below sea level in the Qattara Depression using the difference in head between sea level and the Qattara Depression to generate electrical power. The key to the longevity of the system is the fact that evaporation could balance influx so that the resulting lake in the Depression could be stabilized at a constant level. The last time the study was done, GIS computer software and satellite imaging and elevation data weren't available.

The story line for the students is that the Egyptian government has just hired them to use modern GIS technology to reassess the viability of the project. They want them to 1) provide accurate projections for how much water could be piped from the Med and balanced by lake evaporation at various configurations, 2) estimate how much power could be generated, 3) recommend an optimum configuration for lake level, power station location, holding pond location, and channel/tunnel location, and 4) recommend whether the government should proceed with bidding out a cost estimate for the system.

The four documents posted for downloading consist of a the main project assignment, a preparatory assignment, and several in-class activities that students worked on together. Overall, though, this is not a group project – students work individually.

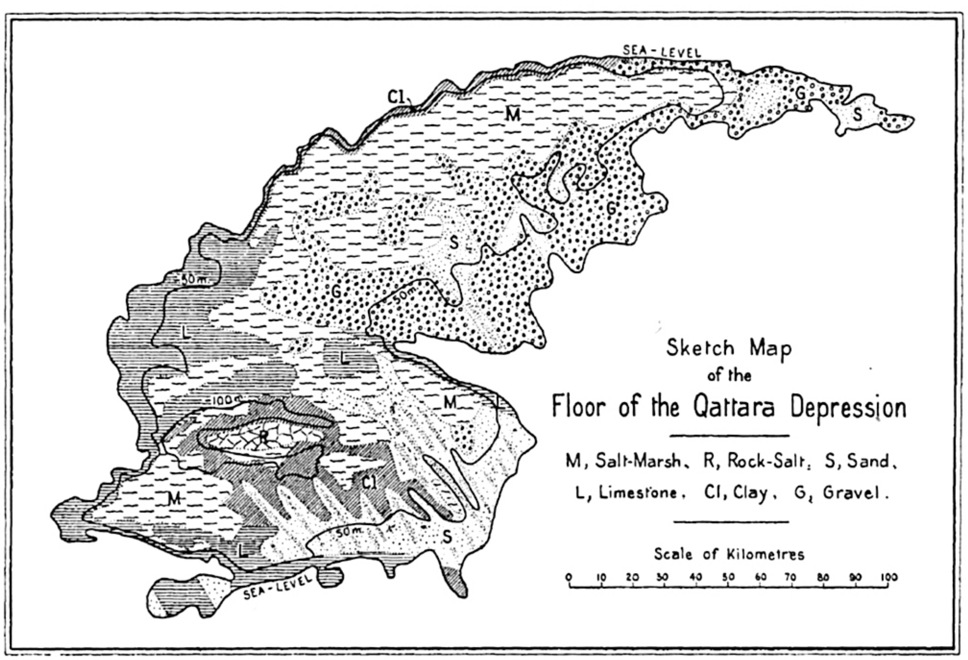
Evaluation: Students will be evaluated on the basis of the thoroughness and accuracy of their GIS analyses and on their assessments of 1-4 as listed above. Students can do the bare bones analysis of 1-4 for a maximum grade of B. To earn a higher grade, they can choose to do additional analyses of the lake/power plant configuration, on the bedrock geology and hydrogegoloy of the Depression, and on the influence of the Depression on the German North Africa Campaign during WWII.

NOTE: This blank page is deliberate and allows the document to be printed double-sided and still have the first page of the exercise start on a separate page.

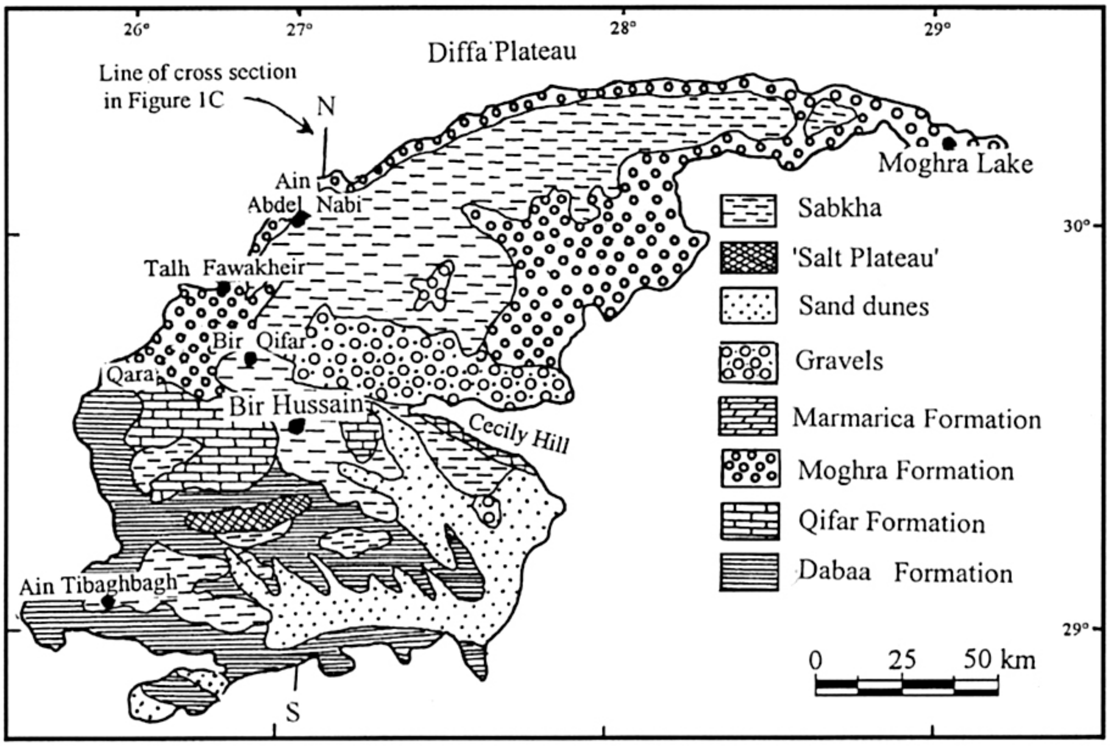
Final GIS Project
The Qattara Depression Solar-Hydroelectric Power Project

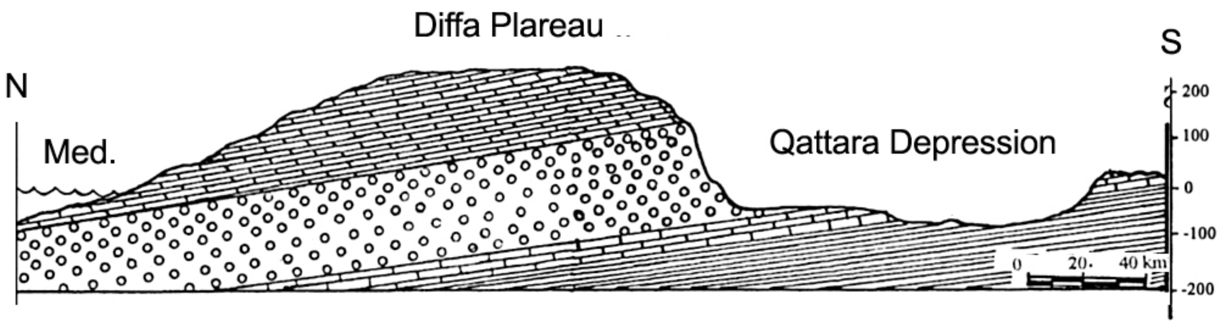
The Executive Summary:

- Several times over the past 80 years, the Egyptians have considered developing a power generating station tens of meters below sea level in the Qattara Depression using the difference in head between sea level and the Qattara Depression to generate electrical power.
- The key to the longevity of the system is the fact that evaporation could balance influx so that the resulting lake in the Depression could be stabilized at a constant level.
- The last time the study was done, GIS computer software and satellite imaging and elevation data weren't available.
- The Egyptian government has just hired you to use modern GIS technology to reassess the viability of the project. They want you to:
  - assess whether enough evaporation could occur to balance the water influx necessary to generate a reasonable amount of power and what the ideal parameters/configuration of the system would be, and
  - make a recommendation about whether the government should proceed with a cost estimate for construction.



(Ball, 1933)





modified from Aref et al., 2002

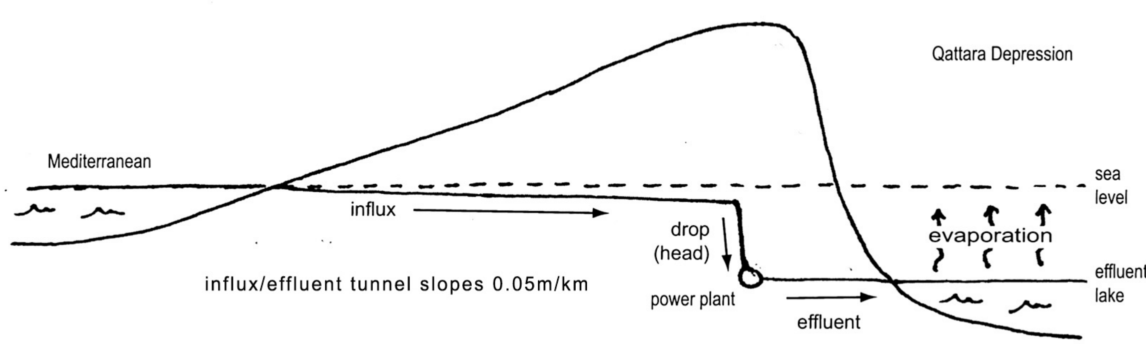
Background

Solar-hydroelectric Power Generation in the Qattara Depression

Beginning as early as the second decade of the 20th century, proposals have arisen several times for an extraordinary solar-hydroelectric power project in northern Egypt in the Qattara Depression. Although the Egyptians are not currently planning to move ahead with the project, they carried out serious feasibility studies in the late 1970s with the enthusiastic support of Egyptian President Anwar Sadat. Israel has also seriously considered a solar-hydroelectric project in the Dead Sea area.

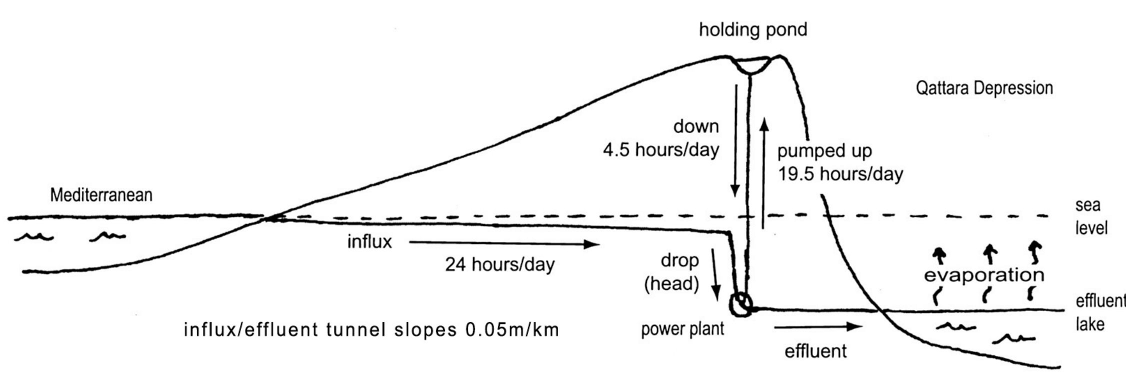
So what is solar-hydroelectric power generation? It's not what you'd think, because the "solar" part doesn't actually play a part in the power generation. Here's how it would work. The Qattara Depression is a closed depression whose deepest point is over 100 m below sea level and whose northern edge is less than 100 km from the Mediterranean. The plan would be to pipe water from the Med to the Qattara Depression. Once the water reached the edge of the depression, it would drop through a power plant built below sea level in the Depression itself.

Well, that's obviously the *hydro* part of the project. What about the solar part? Because the Qattara is a closed depression, a lake would form as water was diverted into the Depression from the Med. Because the area is a hyperarid desert, the lake water would evaporate – that's the *solar* part. The idea is to balance influx from the Med with evaporation of the resulting lake, generating an adequate amount of electricity in a manner that is potentially sustainable for decades, if not centuries. Pretty cool, huh?



The proposal is actually even more interesting than that. Demand for electrical power isn't the same at all parts of the day. At night, for example, demand for electricity is lower than it is at peak demand times during the day. Power plants can generate electricity 24/7, but they can't store electricity during low demand times and save it for distribution during high demand times. Ideally, it would be great to have a system that could easily provide lots of power at high demand times and much less at low demand times. The Qattara Power Project could be designed to do just that.

Here's how it would work. Water from the Med would flow down a canal/tunnel system and into the power station, generating electricity. During off-peak hours, the electricity generated by the power plant would be used to pump the water that has gone through the power station up to a holding pond at the top of the Qattara Depression Rim, more than 200 m above the power station. While the plant was pumping water to the holding pond, it would not be providing any electricity to the grid. When peak power demand time came around, the water in the holding pond would reverse direction and drop through the power plant from above, generating lots of electricity in a short amount of time because it has a large head. The diagram below shows the basic geometry. Despite the fact that the plant would use its own electricity to pump water to the top of the Depression rim, it would do so when the grid doesn't need electricity anyway, which would allow the plant to concentrate its electrical production at times when the grid needed it. This is called a *pumped storage* system.



The Nuts and Bolts of Electrical Power Generation

Electricity is generated by spinning a turbine connected to an electrical generator, a device that rotates a wire coil in a magnetic field and generates an electric current. The turbine can be spun by flowing water, blowing wind, steam, or hot gases. Steam can be natural steam (*e.g.*, a geothermal power plant) or it can be generated by heating water by burning oil or coal, or by the heat generated during nuclear fission. Hot gases can be generated by burning gas.

In a ***hydroelectric*** power plant, a dam creates a reservoir, raising the level of water on the upstream side of the hydroelectric plant, and water drops through the power plant intakes. The difference in elevation between the reservoir and the river downstream of the dam provides the kinetic energy for the water to spin the turbines as the water falls from the height of the reservoir to the height of the river downstream from the dam. The spinning turbines generate electricity.

Electrical power generation is described in terms of **installed capacity in megawatts (MW).**

- Power is expressed in terms of amount of power generated ***per second***. The unit of power, a **Watt,** is defined as 1 Joule of energy transferred in 1 second.
- 1 GW (gigawatt) = 10^3 MW (megawatts) = 10^6 KW (kilowatts) = 10^9 W (watts).
- If a power plant is described as having 2000 MW of installed capacity, it means that, if the plant is operating at peak capacity, it generates 2000 MW of energy per second.
- **Note that power that is generated cannot be easily stored for future use.** If peak demand for power is, for example, 15,000 MW, the grid must be able to supply that amount of energy per second at peak demand time. If off-peak demand is considerably less, any power generated is wasted if the plant keeps running at peak capacity, which is why it is incredibly valuable to have a system that can generate less electricity at off-peak times and more electricity at peak demand time without costly start-up each day.

Current Egyptian Electrical Power Generation

The Egyptians currently have a total installed electrical power generating capacity of 17,700 MW[1]. Egypt's sources of power are as follows (2003 data[2]):

- **Hydroelectric power plants** (15.5% of total, for an installed capacity of 2800 MW)
  - Aswan High Dam: designed for a generating capacity of 2100 MW at full operating capacity. The AHD power project is vulnerable to a series of low flood years, as shown during the drought years of the 1980s when the AHD had a capacity of about 1000 MW when the reservoir was at its low point.
  - Other Egyptian hydro projects make up the other 700 MW of installed capacity.
- **Conventional steam turbine power plants and gas turbine power plants** (84% of total, for an installed capacity of 14,900 MW):
  - A series of conventional steam turbine power stations, mostly in the Delta and at Isma'iliya using coal or oil to generate steam to spin the turbines. Although this type of power generating plant is quite efficient, it is difficult and costly to turn off and on again to cover changes in energy demand.
  - Several gas turbine power stations to cover deficiencies in peak power capacity. Although these can be turned off and on again quickly, they are a much less efficient way to generate electricity than conventional steam turbine power plants.
- **Nuclear power plants**: none currently
  - In September of 2006, however, Egypt announced that it has begun to take steps toward establishing the first nuclear power plant in Egypt.
  - The plant will be constructed by 2020 at El Daba'a on the Mediterranean Coast about 60 km west of El Alamein. If you remember, El Daba'a was one of the locations referred to in the account that you read of British special forces operating in North Africa during WWII.
  - The plant will have a generating capacity of 1000 MW and is expected to cost over $1.5 billion. In June of 2007, Egypt submitted a report to the International Atomic Energy Commission detailing their peaceful nuclear program, and IAEA will eventually present Egypt with a plan for technical assistance.

[1] To put this into perspective, a good-sized city in the US typically needs a power generating capacity of 1000 MW (1 GW). Total installed capacity in the US is 932,000 MW (32 GW) and in Israel is 9,900 MW (9.9 GW).

[2] http://www.iaea.org/inis/aws/eedrb/data/EG-elic.html

Task

You have been hired by the Egyptian government to use modern GIS analysis and satellite data of the Qattara Depression and the area between the Depression and the Mediterranean to:

- provide accurate projections for how much water could be piped from the Med and balanced by lake evaporation at various configurations,
- estimate how much power could be generated,
- recommend an optimum configuration for lake level, power station location, holding pond location, and channel/tunnel location, and
- recommend whether the government should proceed with bidding out a cost estimate for the system.

What you must provide

- A minimum of three well-labelled maps generated in ArcMap that show potential effluent lake areas and power plant/tunnel/channel/storage basin configurations, one showing your optimum configuration, one at a higher elevation than optimum and one at a lower elevation to demonstrate clearly that you have found an optimum level.
- Three cross sections that clearly portray the three configurations and their parameters.
- A brief executive summary that explains the parameters of the three options, makes a recommendation about the best option for optimum power generation, and provides evidence for why that is the best option.
- Additional analyses, if you choose to provide them.
- A recommendation, with rationale and in the context of the current picture of Egyptian power generation, for whether to proceed to a cost assessment.

Ground Rules

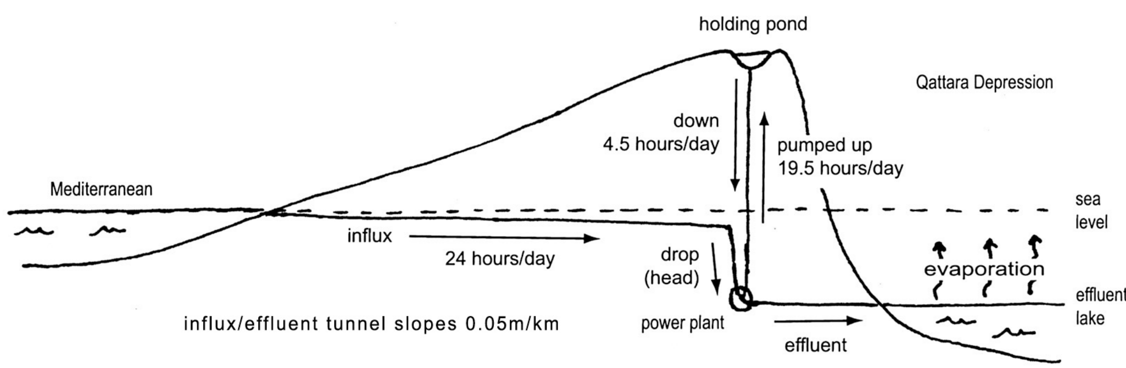
- You must work by yourself. If you have questions, come see me for help, although you must remember that I am going to push you to figure it out for yourself!! I have given you each three cards that you can redeem to find out whether specific numbers you have determined are reasonable or not. Use your cards wisely!
- Your analyses must be your own and must be clearly based on **your own GIS analyses and related calculations**, not on what has been published in various venues and places by others about this and similar solar-hydroelectric projects.

Assumed configuration of the system

There are lots of ways of designing the a solar-hydroelectric project for the Qattara Depression, but we'll assume the following:

- Rather than having the power plant on the shore of the lake, the power plant itself will be located under ground beneath the north rim of the Depression, as shown on the diagram below, in order to accommodate the pumped storage part of the project.
- The power generating plant will be located directly beneath the holding pond in order to allow for maximum drop velocity and power generation.
- The feeder canal/tunnel system from the Med to the power facility and the effluent tunnel/canal system from the power facility to the lake in the depression will have the same slopes (0.05 m/km). The effluent system will end at the elevation of the lake.
- We'll assume that the project is designed to generate electricity from pumped storage for 4.5 hours per day (peak demand time).
- We'll assume that the canal/tunnel system will generate power for 19.5 hours per day to pump water to the holding pond and will contribute to peak-demand power generation for the remaining 4.5 hours.

An effluent lake that is farther below sea level will have the biggest drop and will take less water to generate a given amount of power. But, because lake surface area decreases with increasing depth below sea level, the least water evaporates annually from a lake farther below sea level. So, part of the task is figuring out which lake level and drop optimizes the system.



The Minimum Analysis

Minimum expectation for this assignment

Use ArcMap to determine the following:

- **How big will the effluent lake be?** Experiment with different lake levels to determine the height of the lake that optimizes power generation. Determine the location, surface area, and volume of lakes at three levels, one above the optimum level, one below, and one at the optimum level to demonstrate that you have found the optimum lake level.
- **Where is the best place for the canal/tunnel system?** Determine the best place to put the canal/tunnel complex, holding pond, and the power station for each of the three proposed levels. If there are existing depressions on the rim, and you wish to use one as a holding pond in order to save excavation costs, you need to document that it is big enough.
- **How much water can be evaporated from the effluent lake?** Determine the **net** water loss per year from the lakes at each of your three levels (once they are full), taking into account groundwater influx, local increase in rainfall due to increased humidity, and realistic evaporation rates.
    - Evaporation rates in this part of the northern Sahara are uncertain but have been estimated at 5.5 mm/day (around 20% less than in the Aswan Region), but that's only if the water is fresh water. Brackish and salt water evaporate more slowly, and evaporation rates will decrease with time as salt content rises in the effluent lake. We will use an estimate of 4.6 mm per day as a conservative average that takes into account rising salinity over the first 100 years of power plant operation.
    - A large lake increases local humidity and rainfall, even if it is only by a small amount. Because this is an internally-draining basin, local rainfall that doesn't evaporate outside the lake itself will wind up in the lake, increasing its volume. Natural rainfall, plus increased direct rainfall and local runoff from creation of the effluent lake in the Depression has been estimated at about 0.16 mm/day (slightly more than doubling the normal 0.06 mm/day). Still not very much, but relevant to our calculations!
    - Groundwater does seep into the Qattara Depression and is responsible for the natural sabkha in the basin and the impassable salt bogs that you have read about. Influx of groundwater into the depression is estimated at 1 km^3/year across the basin, principally in the area that will hold the effluent lake (*i.e.*, groundwater influx will add to the effluent lake volume, rather than evaporate away into the air, as it does now).
- **How much water could we let in to the lake from the Med every year?** If we want to maintain a constant lake level, once the lake is full, then the amount we let in from the Med every year has to equal the amount lost by evaporation. Determine the maximum influx in millions or billions of m^3/year to the lake that could be exactly balanced by the **net** loss by evaporation at each of your three lake levels (once they are full) and the corresponding maximum allowable flow rates in m^3/sec through the canal/tunnel system.

- **How much power could the canal/tunnel system generate?** Determine the generating capacity in MW for the tunnel/power plant system at each of your three lake levels. Power generated is easy to calculate using the following formula, because 1 KW is equivalent to 102 kg-m/sec and is a function of the density of the fluid, the flow rate, and the drop through the power station:

  $$rQH/102 = \text{KW of generated power}$$

  where:
  Q = flow rate of the water in m^3/sec
  H = the height of the drop through the power station in m
  r = the density of seawater, which is 1027 kg/m^3
  (converted from the usual units of 1.027 gm/cm^3)

  Remember that you need the answer in MW and that 1 MW = 1000 KW. The number calculated using the formula above would be true only if the power plant were 100% efficient, which it isn't. In calculating a realistic number for the total installed capacity in MW, assume that the power plant is 90% efficient.
- **How much power could the pumped storage system generate?** Determine the capacity in MW for the pumped storage part of the system at each of your three lake levels that could be generated by emptying the holding pond each day. Use the formula in the previous bullet, but calculate a flow rate from the estimate that the holding pond can store about 15 million m^3 of water to be released each day over a 4.5 hour time period. As with the previous question, assume 90% efficiency in generating power from the pumped storage system.
- **What is the optimum configuration?** Present your view concerning what the optimum lake level would be. Factor in all of the parameters that relate to power generation. Are there any obvious construction issues that differ between options that influence the best choice?
- **Should the Egyptians proceed?** Present your recommendation to the Egyptians. Does this project compare favorably enough at peak capacity to other aspects of Egyptian power generation to be worth considering?

Beyond the Bare Bones

Additional options

Pages 9 and 10 outline the minimum necessary to complete the assignment. If you do what is outlined on those two pages, the maximum grade you can earn is a B-, a perfectly respectable grade! If you want to have a shot at a higher grade, you can choose from the following outstandingly interesting options for an additional 1/3 of a letter grade for each option. In other words, if you do one of the options below in addition, the maximum grade you can earn is a B. Do two, and the maximum grade is a B+, and so on. A shot at an A+ requires that you do five of the eight below. If you're really motivated, you can earn extra credit for doing more than five.

- **Canal or tunnel or both?** The project needs to get water from the Mediterranean to the power plant and from the power plant to the lake edge. Canals are cheaper to construct than tunnels, but only up to a point. The farther the canal bottom lies below the ground surface, the more material has to be excavated to create the canal. Let's estimate for this project that the break-even point occurs for a canal whose bottom lies 30 m below the *ground* surface. Where could the project use canals and where would tunnels have to be bored, and what are the lengths of each segment for each of the three options? How might what you have learned in this question influence the choice of the best option?
- **How big a tunnel?** The slope of the tunnel is very low (0.05 m/km), and the water in the tunnel won't be moving very fast (only about 2 m/sec). But we need to move a lot of water through the tunnel. The way to move large volumes through at low velocity is to have a big tunnel. So, how big is big? How big would a tunnel have to be to handle the needed flow rate? If the needed diameter is too big for one tunnel, how many tunnels of what size would it take to carry the water to the power plant? Assume a flow velocity of 2.0 m/sec, and assume that the maximum diameter tunnel that can be constructed is about 15 m.
- **Filling the lake with salt!** We worried about how long it would take Lake Nasser to silt up, but our effluent lake doesn't have that problem because the incoming seawater will be carrying negligible suspended sediment. But, the seawater *will* be carrying dissolved salts, and, with evaporation of the lake, the lake water will eventually become saturated with salt. After the lake water becomes saturated, salt will continuously precipitate and accumulate at the bottom of the lake as new sea water comes in and evaporates. How fast will salt accumulate? Will it accumulate fast enough to put a crimp in the longevity of the system? Here are some stats that will help you figure it out:
  - Mediterranean sea water contains 3.77% by weight of dissolved salts. This means that, if you evaporated 100 grams of seawater, you'd generate 3.77 grams of salts (phrased another way, the seawater required weighs 26.5 times as much as the salt produced).
  - If seawater and salts were the same density, it would also take 26.5 times as many m^3 of seawater to produce a given volume of salts. But, because salts are 2.2 times denser than seawater, it actually takes 2.2x26.5, or about 58 times as many m^3 of seawater to produce a given volume of salts.

- **Does the tunnel system as proposed generate enough electricity to lift the required water to the holding pond?** The proposal requires that we can pump 15 M m^3 of water to the holding pond on the upper rim of the Depression in order to generate significant quantities of electricity at peak times. Does flow from the Med for 19.5 hours generate enough electricity to actually lift that amount of water to the holding basin? Here are some hints to get you going. There's also a very nice Danish web site that has very clear descriptions of energy and power units at http://www.windpower.org/en/stat/unitsene.htm.
    - You can't get something for nothing. The total number of MWh (megawatt hours) of energy produced over 19.5 hours by the tunnel system and used to pump water to the holding pond (minus 10% for losses during pumping) is equal to the amount of energy in megawatt hours that you can expect to generate by dropping that same pumped water back through the power station for 4.5 hours (again minus 10% for efficiency losses).
    - Megawatt hours are calculated simply by multiplying generating capacity in MW times hours. You do need to worry about megawatt-hours to solve this problem, because the number of hours is different (19.5 vs. 4.5).
    - For comparison with what you calculate, you've already determined how many MW of power (not MWh) the project is designed to generate (i.e., what they would like to get) from the pumped storage part of the system.
- **If the power that can be generated by the tunnel system isn't enough to pump all the water to the holding pond, how much off-peak power will have to come from Egypt's grid?** If you determined a deficit in the question above, this isn't necessarily a showstopper for the project, because the project could use off-peak, unused power from elsewhere on the grid to augment what could be generated locally in the Qattara project. But how much would it take in MW, and is this a reasonable number to get off the grid in off-peak hours?
- **How long until the lake reaches equilibrium level?** The effluent lake obviously won't fill immediately, and it's a rather complicated thing to figure out how long it would take to fill. Qualitatively, what will the rise pattern of the lake be like over time, and how would you go about determining how long it would take for the lake level to reach the equilibrium level set for the project? You don't actually have to make the calculation.
- **What is the geology of the Qattara Depression, and how has it evolved to an area so far below sea level (which is what makes the power generation proposal even possible!)?** Read up on the geology of the Qattara Depression (refs provided on Blackboard)[3], and write a short **illustrated** description (or do a concept sketch) on the role of the groundwater table and wind erosion in the evolution of the Qattara Depression, and add it as an appendix to your report.

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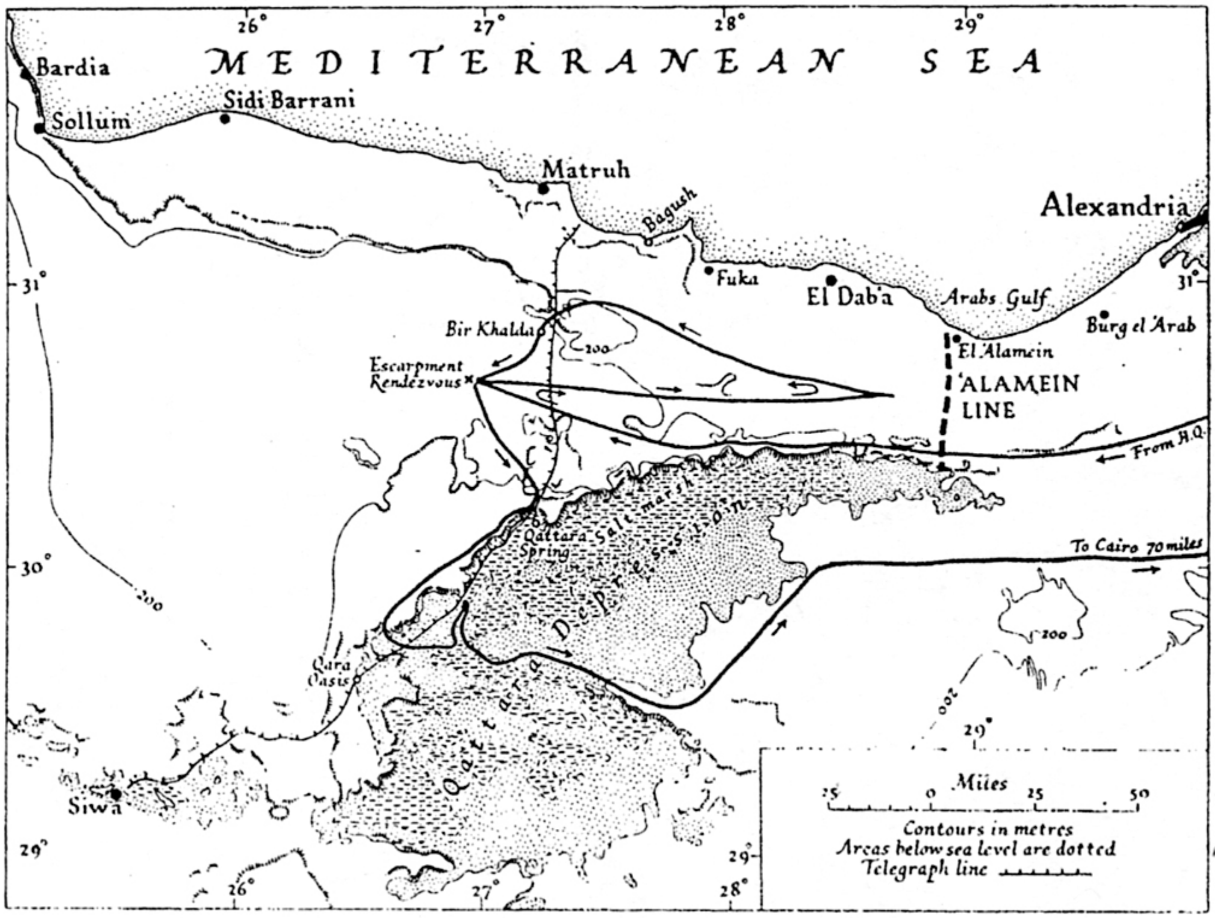
[3] Albritton, Claude C., Brooks, James E., Issawi, Bahay, and Swedan, Ahmed, 1990, Origin of the Qattara Depression, Egypt: Geological Society of America Bulletin, v. 102, p. 952-960.
Aref, M.A.M., El-Khoriby, E., and Hamdan, M.A., 2002, The role of salt weathering in the origin of the Qattara Depression, Western Desert, Egypt: Geomorphology, v. 45, p. 181-195.
Abdoiu, El Bassyony, 1995, Introduction to the geology of the Qattara Depression: Cairo, Egypt, International Conference on the Studies and Achievements on Geosciences in Egypt, p.85-99.

- **How did the Qattara Depression influence the German North Africa Campaign of WWII?** Pull together what you have learned from reading the account of the British special forces[4], from Col. Hensley's lecture, and from what you know about the formation of sabkhas and salt quicksand bogs to write a short **illustrated** description (or do a concept sketch) of the influence of the Qattara Depression on the military options and hence the outcome of the Battle of El Alamein during WWII. Add this as an appendix to your report.



Mather, 1944

What you will turn in

Electronic files on the software server

- **IMPORTANT!!** Before you start your project, go to ArcCatalog and create a new folder **inside** your folder in Geosc 103 into which you can put all of the files related to this project. If you mix your files in with all of the files from earlier in the semester, it will be hard for me to find the ones related to this project. **Saving relative pathways:** Be sure, **before** you add anything to a new ArcMap document that you change the Data Source Options to **Save Relative Pathways**.

[4] Mather, D.C.M., 1944, A journey through the Qattara Depression: The Geographical Journal, v. 103, no. 4, p. 152-160.

- **File management:** If you make any DEMs, hillshades, shapefiles, etc. that you don't use in your final .mxd file(s), please go to ArcCatalog and delete them from the TOC so that your project folder consists **only** of the files that you are actually using.
- **Deleting files to make space in your folder on the server:** Depending upon how much stuff you have added to your Geosc103 folder, you may find that you run out of space as you are working on this project. If you want to delete files from earlier in the semester, you can do that, but **be sure that you go to ArcCatalog and delete the files from the TOC in ArcCatalog**, rather than just opening up your folder on the server and trashing files. If you do it through ArcCatalog, it will automatically delete all of the accompanying files that need to be deleted but that you could easily miss if you did it the other way.

Hard copy

- Three ArcGIS maps (beeyouteeful ones, with labels, scale bars, etc.), one for each of your lake levels, showing the system configuration and parameters. Be sure that each has a legend, scale, north arrow, and key.
- Three cross sections, one for each of your lake levels, showing the system parameters. If you want to incorporate your cross section into your ArcMap, that would be lovely. But, hand draw cross section sketches are fine, too. I'm happy with hand labeling, though!
- Executive summary and rationale as described on page 7.
- Supporting calculations as appendices.
- Optional analyses as desired.