DEVELOPMENT AND MANAGEMENT OF WATER RESOURCES

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1. INTRODUCTION

The lack of suitable supplies of water lies at the root of many of the difficulties experienced by developing countries. Besides fulfilling basic life requirements, water availability is a cornerstone of satisfactory sanitation, public health, agricultural production, industry, recreation, environmental maintenance, and urban development. Unfortunately, the development of major water works is beyond the capability of single individuals, so here more than ever there has to be an integrated effort between user communities, the scientists and engineers that design and construct the water works, and the public agencies that help fund and manage such works.

In this paper we take a bird's eye view at the technical aspects of development of water resources, from direct use of surface waters to tapping of groundwater. Throughout this paper we have relied heavily on the Ethiopian experience as the source of our examples because Ethiopia typifies the conditions of many developing countries in terms of infrastructure, technical expertise, agricultural and industrial development, and scope of its public agencies. Furthermore, the geology, topography and climatic conditions of Ethiopia range over such extremes that lessons learned within it have almost universal application. A summary of the geology and hydrogeology of Ethiopia is thus a good starting point for this discussion.

2. SUMMARY OF THE GEOLOGY OF ETHIOPIA

Ethiopia is a country with a broad range of geomorphic provinces (Figure 1a): A high and rugged mountainous core—cut by deep gorges and incised river valleys—, fault-bound plateaus and basins, a prominent rift valley that hosts a number of lakes, and bordering plains that range from the harshest of deserts to subtropical jungles. Elevations range from 4620 m above mean sea level at Ras Dashen to 110 m below mean sea level in the Afar depression.

In terms of their surface exposure, the main lithologic units of the country have been grouped in (Tefera et al., 1996; Tamiru Alemayehu, 1993; Mohr, 1983) (Figures 1b and 2):

- Precambrian metamorphic basement rocks (cover about 23% of the surface of the country).
- Mesozoic sedimentary rocks (cover about 25%)
- Tertiary volcanic rocks—largely flood basalts— (cover about 25%)
- Quaternary volcanic rocks—largely ignimbrites—and sediments (cover about 17%)

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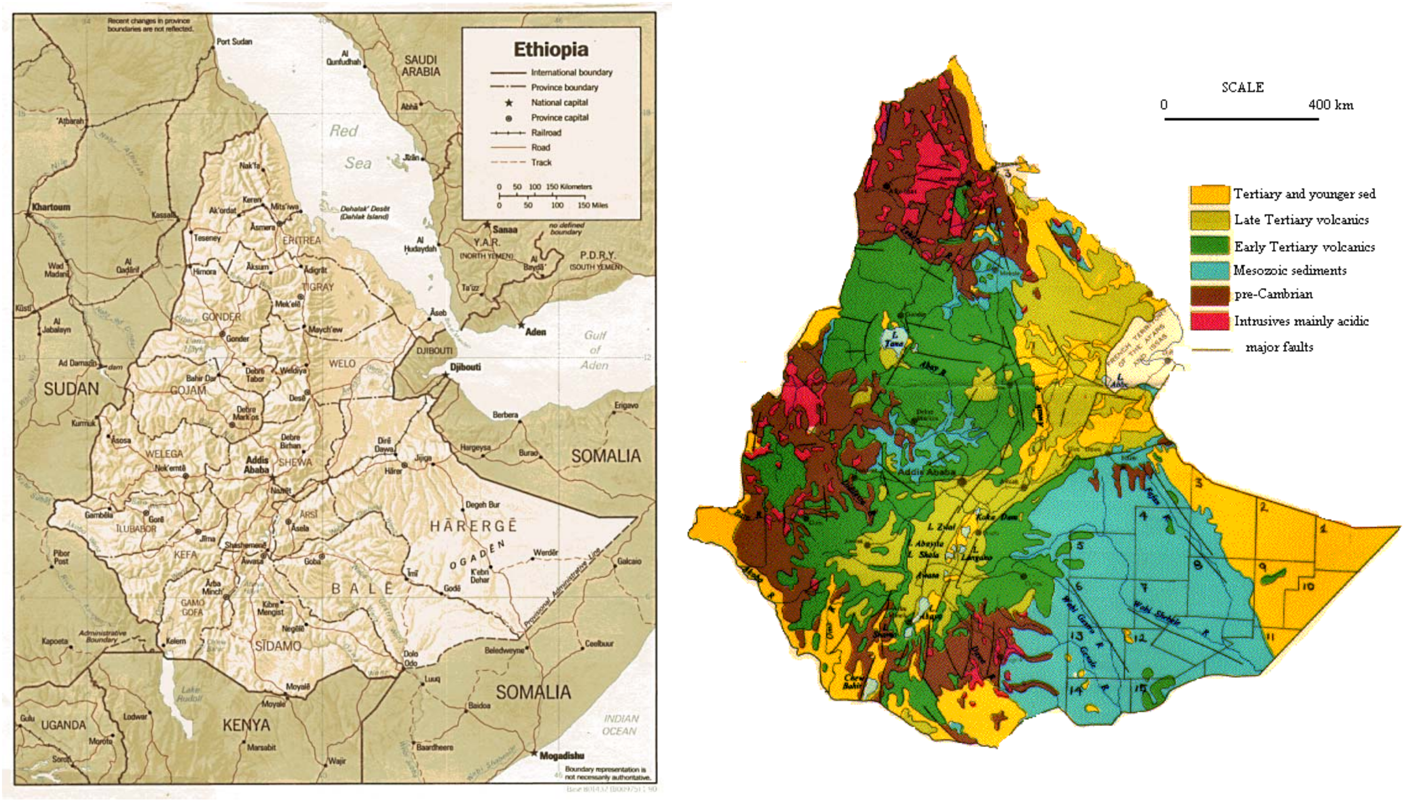

Figure 1. (a) Geomorphology of Ethiopia. (b) Geologic map of Ethiopia.

Precambrian metamorphic rocks are exposed in the northern portion of the country (hereafter referred to as the northern complex), the west (the western complex), and the south (the southern complex) (Figure 1b). The northern complex represents a lower grade of metamorphism, and in it is common to find slates, schists, and meta-igneous rocks. The metamorphic rocks have been intruded by a series of phonolite stocks in the neighborhood of Axum. The southern and western complexes display a higher grade of metamorphism, and in them the dominant lithologies are gneisses, pyroxene granulites, and migmatites.

At the end of the Precambrian the craton was uplifted, so very few Paleozoic sedimentary rocks are found in Ethiopia. Conditions changed at the onset of the Mesozoic, when shallow seas spread initially over the Ogaden region and then extended further north and west as the land continued to subside. Sandstone was deposited on the old land surface, followed by the deposition of shale and limestone as the depth of water increased. In the west of the country, sedimentation ended up with the deposition of clay, silt, sand and conglomerate as the sea receded during the Jurassic. Gypsum and anhydrite precipitated on intertidal flats in some parts of the country. The sea invaded again in the lower Cretaceous, and the sedimentation sequence was repeated, ending again with the precipitation of gypsum and anhydrite beds. As shown in Figure 2, Mesozoic rocks are prevalent in the southern portion of the country, and around the margins of the central massif.

The Mesozoic units are too numerous to detail in this paper, but three units are common enough throughout the country to merit a brief description. From bottom to top they are:

- *Adigrat Sandstone*. Triassic to lower Jurassic in age, this sandstone is medium to coarse-grained and red to brown in color. It is a well sorted, massive, cliff-forming sandstone with an average thickness of about 800 m.
- *Antalo Group*. The three formations of the lower to middle Jurassic Antalo Group are calcareous, and as discussed later are both a prime target aquifer and a major headache in dam construction. The three formations of this group are known as the Abbay Formation (interbedded shales and limestones), the more massive Antalo Limestone, and the Agula Shale.
- *Amba Aradom Formation.* This upper Jurassic to lower Cretaceous formation consists of interbedded sandstone, shale and marl, deposited conformably on the rocks of the Antalo Group. The rocks become progressively coarser in grain size southwards, until the sequence becomes dominated by conglomerates toward the southern border of the country.

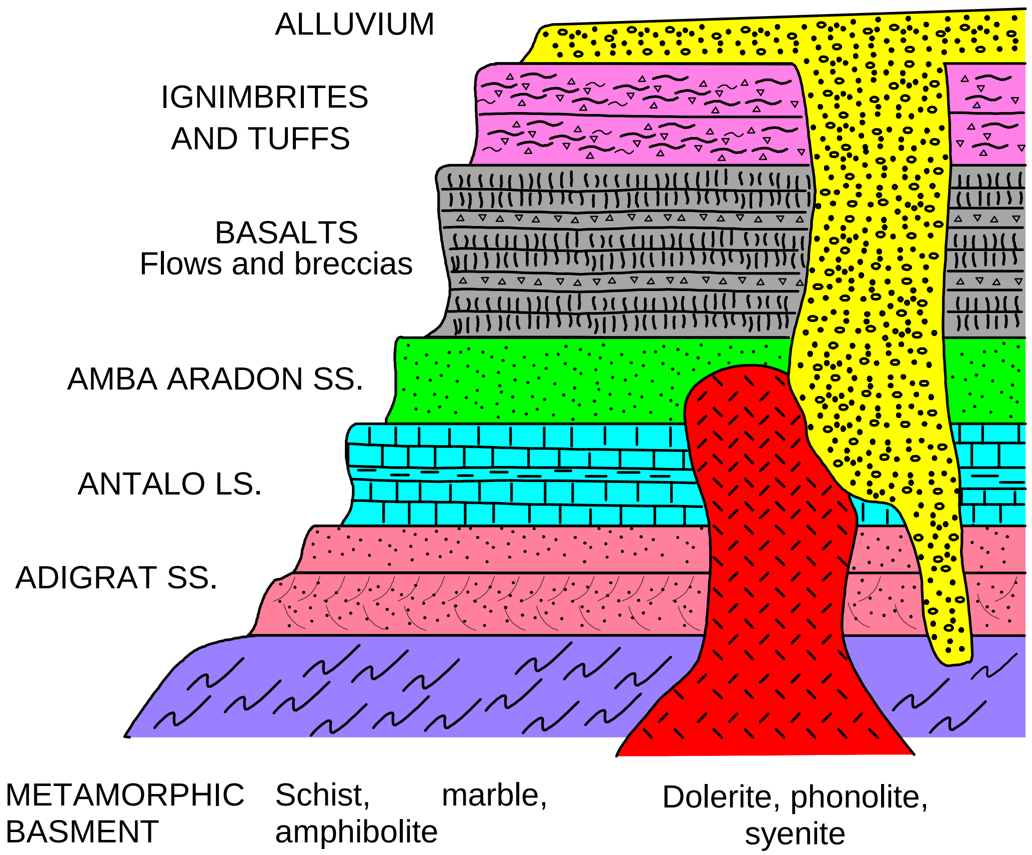

Figure 2. Simplified stratigraphic column of northern and central Ethiopia.

The development of the Ethiopian hot spot, which eventually was going to lead to formation of the Afar triple junction, dates back to the early or middle Tertiary. Its surface expression was the outpour of voluminous basalt flows, which stacked one upon the other to form a sequence that is now thousands of meters thick. These flood or "trap" basalts now form the mountainous core of the country, variously referred to as the central massif or the central plateau (Figures 1 and 2). These lavas can form important aquifers, and can also cause leakage problems in reservoirs (but these problems can be solved through selective grouting).

Shallow basaltic (diabase) intrusions, probably related to the same pulse of flood basalt magmatism, cut through the Precambrian and Mesozoic rocks. These dikes, sills and stocks partition the limestone aquifers of the Antalo Group into sub-basins, and play a crucial role in the siting of artificial reservoirs and dam structures, as discussed below.

At a continental scale, the eruption of flood basalts went hand in hand with the development of a large-scale, elongated swell of the Afro-Arabian region, which eventually "tore" into three rifts: the Red Sea Rift, the Gulf of Aden Rift, and the East African Rift. According to Kazmin et al. (1980), rifting started at the triple junction in the Miocene (about 15 million years ago), and from there extended south in a series of rifting episodes at 10, 5, 4, 1.8 and 1.6 million years ago. Each stage of rifting and downfaulting was accompanied by bimodal volcanism in the rift (basaltic lavas, and trachytic and ryholitic ignimbrites). The effects of tectonic extension went well beyond the axis of the rift, so basaltic and trachytic shield volcanoes are common on the rift shoulder and margins. The capital city of Addis Ababa is built atop such a marginal sequence of rhyolitic ignimbrites (the Nazret Series).

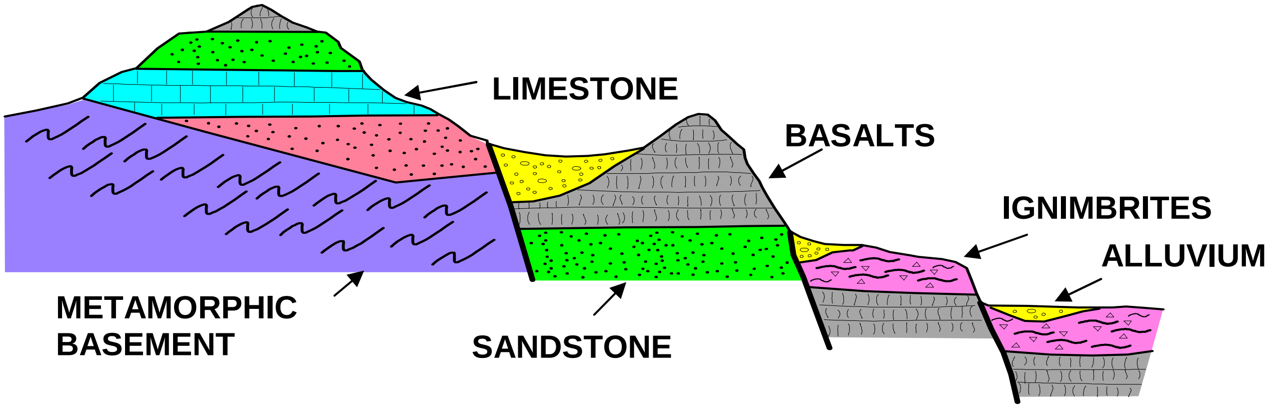

Figure 3. Schematic cross section from the central massif to the Rift Valley.

As Figures 1b and 3 show, the normal faults of the East African Rift extend far from the axis of the rift into the central massif, and are thus directly responsible for steep mountain flanks, high-energy streams, and a good number of alluvium-filled grabens. All these features have a direct bearing on the development of water resources, as discussed in the next section.

3. HYDROGEOLOGY OF ETHIOPIA

As a mountainous country, Ethiopia receives a significant amount of rainfall in the highlands (Figure 4), and even in the arid areas rainfall can be used as a direct water resource if efficiently harvested and properly stored. At a broader scale, the abundant rainfall feeds the groundwater system and streams that go from small seasonal rivulets to the mighty Blue Nile. In short, there is no shortage of water in the country, which has been dubbed “the water tower of Africa”. But most of this water evaporates, runs away as stream flow, or is stored beyond reach in aquifers. The latter is a latent resource that is closely linked to the subsurface geology, as shown in the following paragraphs.

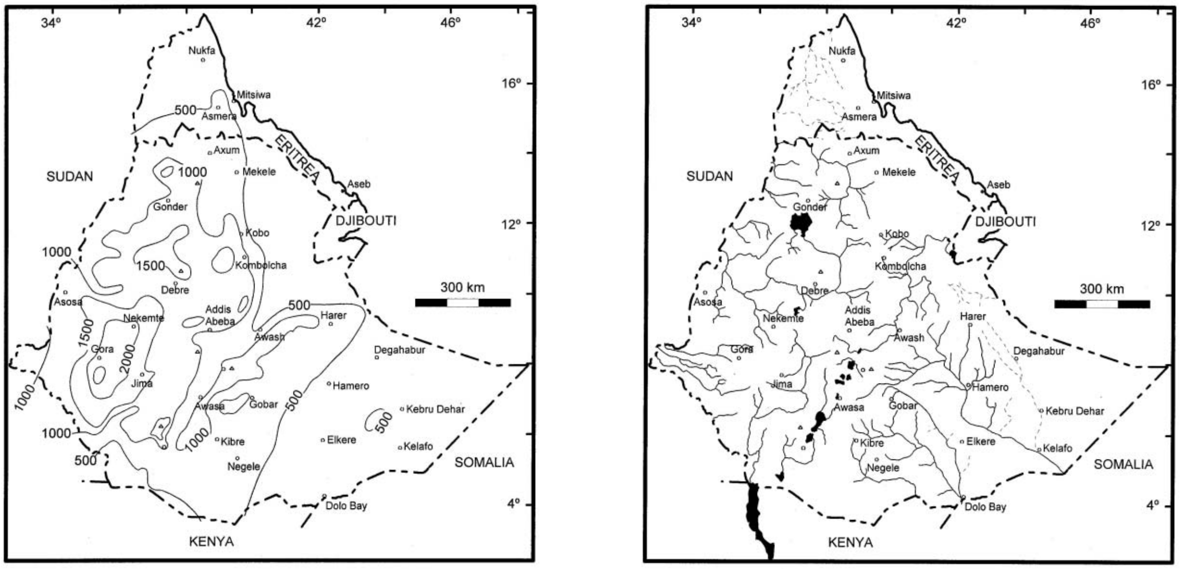

Figure 4. (a) Contours of mean annual precipitation in Ethiopia, in mm (modified from Chernet, 1988). (b) Major rivers (bold lines) and dry washes (thin lines) of Ethiopia. Lakes are shown in solid black, and triangles indicate major mountain peaks.

From the standpoint of groundwater development, the rocks of the Precambrian metamorphic complexes are notoriously problematic. Fractured-rock aquifers exist within them, but in their shallow reaches can only produce very modest amounts of water, often barely sufficient to satisfy the drinking needs of small settlements. The deeper reaches of these aquifers could have higher yields, but exploration and deep drilling will be expensive and time consuming.

The Mesozoic sequence is much more promising in terms of groundwater development. For example, springs are often found at the contact between the Adigrat Sandstone and the Precambrian basement rocks (Figure 3), so this contact is a key exploration target. As far as large-yield aquifers go, the limestones of the Antalo Group are by far the most promising exploration target. They have prominent secondary permeability in the form of solution cavities, and their stratigraphy is laterally continuous over relatively large distances. The northern city of Mekele, for example, derives its potable water from a well field developed in limestones that have been intruded by basaltic (diabase) dikes and stock.

Unfortunately, the same characteristics that make the Antalo limestones a good target for groundwater exploration also make them a major headache for the engineers involved in construction of artificial reservoirs. To put it simply, the losses due to infiltration into the karstic substrate are so large that some reservoirs are at best seasonal recharge basins for the underlying aquifers. Small screens of limestone caught between diabase intrusions could be dealt with by grouting or clay blankets, but where limestones are the prevalent lithology it may be best to abandon the leaking reservoir in favor of a new location.

The Tertiary flood basalts can be major sources of groundwater, which under some circumstances are easy to tap. For example, high-yield springs are common at the contact between the flood basalts and the Mesozoic rocks (Figure 3), and at the rubbly contact between individual lava flows. Furthermore, many springs are high enough above the valley floors that water can be delivered by gravity with relative ease. On the other hand, most springs have modest yields so they are not a viable alternative for irrigation water or larger settlements. Extraction through wells would undoubtedly afford higher yields, but drilling through these hard rocks is beyond the current technical capabilities of Ethiopia. We have recommended excavation of horizontal galleries (in essence horizontal wells) as a viable alternative for generating higher yields. Driving galleries is not trivial, but the rubbly contacts between lava flows are not as hard as the columnar-jointed flow interiors, water collected in galleries can be distributed by gravity (hence bypassing the need for costly pumps and the energy needed to run them), and there is enough mining going on in the country that there is a small number of miners that could be trained to be crew leaders.

The aquifers hosted by the late Cenozoic volcanic sequence, dominated by ignimbrites and tuffs (Figure 3), are not as “consistent” as those found in the flood basalts, although they too are in essence fractured-bedrock aquifers. The difference arises from the fact that columnar-jointed basalts have excellent vertical permeabilities, and the rubbly zones form laterally extensive water storage zones. In contrast, ignimbrites are not as extensive, their vertical permeability is not as high, and they do not have predictable “target” zones for groundwater exploration (unwelded intervals of an ignimbrite would form excellent aquifers, but such intervals are not always present). Nonetheless, deep wells that intersect a good number of water-bearing fractures can have very good yields. Furthermore, drilling through ignimbrites can be easily accomplished with simple wire-line drilling tools (which can be manufactured locally), hence bypassing the need for sophisticated imported drilling rigs.

The Cenozoic sedimentary units host some of the most promising groundwater resources. Targets for exploration include:

- Alluvium-filled grabens
- Channel fills
- Coarse sandstone and conglomerate layers interbedded with shales
- Contacts between clastic and chemical sediments
- Contacts between clastic sediments and interbedded volcanic rocks
- Lava flows interbedded within lacustrine sedimentary sequences

Groundwater development in alluvium-filled grabens has the highest potential for making a difference in further development of the agriculture of Ethiopia, because these valleys are scattered throughout the mid elevations of the country—where most of the population lives—, they are recharged every year by mountain streams, many are “full to capacity” so their water tables are shallow, and they are filled with coarse-grained alluvium with good hydraulic conductivities. Of course, groundwater development requires power to pump the water out of the ground, and the power infrastructure of Ethiopia is very limited. While the power infrastructure builds up, then, it would be best to promote pumping systems based on wind power, small internal-combustion engines, or even hand-pumped systems.

Another advantage of developing groundwater aquifers in alluvium-filled grabens is that exploration is straightforward and has a high chance of success. Seismic and electric geophysical methods will normally allow fairly accurate estimates of the depth to the water table, and drilling can be easily accomplished with simple wire-line tools that can be manufactured locally. Perhaps the major challenge is the planning of the rational development of the basin. Taking a page from California history, small basins like the Santa Clara Valley can support a prosperous agricultural industry, but only as long as the extraction is controlled to avoid rapid loss of artesian pressures, or pronounced drops in the water table (see Ferriz, 2001, for a description of California’s hydrogeology).

4. STRATEGIES FOR DEVELOPMENT OF WATER RESOURCES

Harvesting rainfall

Rainfall distribution patterns are strongly controlled by latitude and orographic relief, as shown in Figure 4a, and vary from a high average value of more than 100 cm per year (36 inches) to a low of 10 cm per year (4 inches). Rainfall distribution is strongly seasonal, with a “big” season in spring, and a “little” season in late autumn (Figure 5), and has the normal variability expected from a stochastic process. In other words, there are “average” years, “wet” years and “dry” years like anywhere else in the world. Incidentally, in Ethiopia the “water year” coincides with the calendar year (January 1 to December 31).

Not surprisingly, the lowest precipitation is prevalent in the arid regions of the country, which in consequence have an almost total absence of surface water (with the prominent exception of the large rivers that have their origins in the mountains—for example, the Omo River in the south or the Wabe Shebele in the east—or the lakes of the East African Rift). And yet, the inhabitants of the desert rely on the harvesting of the meager rainfall to meet their basic drinking needs. Rainfall harvesting is the simplest of water development strategies, and a simple calculation will show that 10 cm of rain, collected over a surface of 1 hectare (100 by 100 m), would yield a total of 1,000 m^3 or 1,000,000 liters (as a rule of thumb, for basic human needs one would hope for an absolute minimum supply of 10 liters per day per person, so our 1,000,000 liters per year would be able to support a community of a couple hundred people year round).

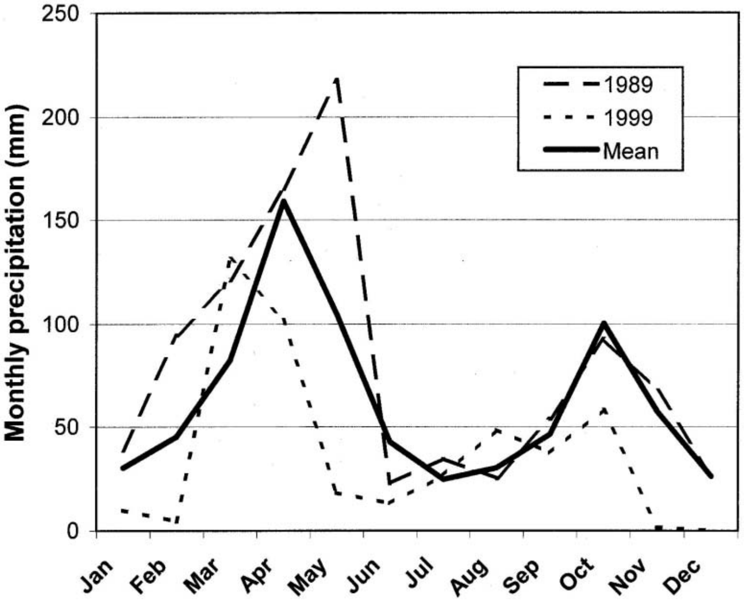

Figure 5. Rainfall hyetographs for Konzo, in southern Ethiopia. Mean refers to the period between 1989-2000. The wettest year on record was 1989, and the driest was 1999.

Creating a collection surface of 1 hectare is not as difficult as it may seem at first sight: a well swept rock outcrop on a gentle slope will perform duty admirably, and with a little forethought and a rudimentary fence the area can be kept reasonably free of contaminating organic matter. The main problem is where and how to store 1,000 m^3 of water. Without going into specifics, it can be stated that such storage cannot be accomplished effectively in open reservoirs or above-ground tanks, which leaves the alternative of storing it underground. This solution is not novel. For example, the *karez* are infiltration galleries that have been used in Iraq and Iran for centuries to serve the double purpose of harvesting groundwater and storing it. The main difference between these hand-dug galleries and modern storage tunnels is scale. A typical tunnel might be 4 m in diameter and only 100 m long to provide storage for 1,000 m^3 of water. Such a tunnel could be easily built in a couple of weeks by standard drill-and-blast methods.

Use of surface waters

Rivers

Rivers are obvious sources of water in a mountainous country, but steep gradients make river engineering a challenging endeavor. We address the issue of reservoir construction in the following section, so here we limit our comments to direct withdrawal of river water for irrigation purposes. A commonly used strategy to achieve this purpose is to build a low embankment, or weir, to raise the water level by a meter or so, and then have an intake structure in the pool formed behind the weir. Water is taken by gravity and fed into a primary irrigation channel.

The problem that this simple scheme finds, at least in a mountainous country where tectonic uplift continuously rejuvenates stream gradients, is that the river tries to eliminate any obstacles in its path by either burying them under alluvium, or by abrading or pounding them to pieces with the help of its transported bed load. Additionally, the high energy flows of the rainy season often tend to bypass any in-channel engineering structures by cutting into its banks, which in turn might lead to loss of valuable farmland. Strategies to manage these problems include:

- Reduce the transported load of the river by erosion management in the watershed.

- Off-river intake structures. To implement this strategy, a gallery is excavated parallel to the river, preferably along a highly permeable gravel bar or channel bank, at a point upstream that is at least 5 meters higher than the origin of the primary irrigation channel. The gallery does not need to be very deep (1 meter below water level in the river should suffice), and a gravel "sausage" is built within it–0.5 to 1.0 m in diameter, 10 m long and with a 3% gradient. The lower half of the "sausage" is lined with a heavy plastic that drains into a 10 cm pipe that conveys the collected water to the primary irrigation channel. A limitation of this strategy is that the gallery could be left "hanging dry" if the water level in the river were lower than anticipated, or if the river were to "jump" its channel away from the gallery. Some of these problems can be circumvented if instead of a gallery one builds a deeper large-diameter well (say 1 m in diameter and 5 meters deep). The well, of course, would have to be provided with some type of pump, so the advantages of gravity-feed would be lost.

- Use a rock ramp to gradually reduce the gradient and dissipate the energy of the river before it reaches the weir. The rock blocks are large in size, and act both as armor to the channel and energy dissipators. This technique has been used in low gradient (<3%) rivers in California and Europe, and their design is reasonably well understood (e.g., Whittaker and Jaeggi, 1987).

- Construction of protection cages, both upstream of the weir and around the intake structure. Such cages have been built in Japan as part of the structures called Sabo dams, usually out of railroad rails or steel beams of equivalent strength. This is the "brute force approach" and is generally not advisable because of cost and unpredictable “side effects” (such as scour of the banks around the protection cage). It may be, however, the only alternative for “rescuing” a structure that is being pound to pieces.

- Build the weirs with drop-in structures that reside in the stream only during low flows, which is also when irrigators tend to divert water. The weirs are built by stacking gabion blocks (cages of chain link fence filled with angular, well-graded gravel) with help of a boom. The weirs are removed before the onset of the rainy season (when irrigation is not needed, anyway), and are stacked on the banks for re-use during the next dry season. By removing the weir one makes use of the “flushing” capability of the river to keep the channel deep and open, thus helping to avoid avulsions (i.e., sudden changes in channel position). We believe that this strategy is one of the best compromises for developing countries, in that cost is low, design is simple, and long-term environmental impacts are minimal.

To conclude this section we would like to mention that trying to control the avulsions of a sediment-laden, energetic river is definitely not trivial. Perhaps the best approach is to remain vigilant to make sure that the channel that we are familiar with remains that path of least resistance. This may imply periodic clearing of mid-channel bars (ideally during the dry season) and log jams, and construction of simple rock dams across older channels of the river. These are not simple tasks in themselves, but they are also well within the capabilities of a community effort.

Reservoirs

Construction of reservoirs is a reasonable alternative to increase the residence time of water draining off the land. Unfortunately, construction of a large dam is costly (i.e., it often requires international funding), and neighboring countries may feel that such an impoundment infringes on their own use of that water. As a consequence, developing countries may encounter great difficulty in raising the necessary funds for such a project. Here we address the construction of small to medium size reservoirs (where small implies construction of dams that are less than 10 meters in height, and medium size refers to dams that are between 10 and 50 meters in height).

To be useful, a reservoir that impounds water for drinking and irrigation supply must

- Impound enough water to meet the needs for which it is being constructed (which in turn means that enough water must be available to fill the reservoir)
- Store the maximum quantity of water possible with the smallest dam practicable (and materials must be locally available to build the dam)
- Have a minimum of leakage (which in turn means that the rocks in the inundation area must be impervious, and the dam itself must be sited where it will have a sound foundation)
- Be sited where the water stored can be put to the best use (preferably without having to pump it)
- Be sited where the water stored can be kept reasonably free from pollution
- Not pose an undue risk to downstream communities

- o Be constructed and operated at a cost that is reasonable given the expected benefits from the impoundment of water

The design team must gather a significant amount of basic data to site and design the reservoir so it best meets these goals. Here we are concerned with the type of data that are gathered by the engineering geologist, but acknowledge the important role that other specialists play in the design team (including civil and mechanical engineers, land-use planners, water purveyors, and financial analysts). Within the broad spectrum of design activities, the engineering geologist plays a crucial role in: preliminary regional studies, hydrologic studies, geologic studies of the inundation area, foundation and seepage analysis of the dam structure (sometimes including stability analysis and design of foundation improvement measures), foundation analysis of appurtenances (sometimes including hydrologic studies for spillway design), and on-site professional support during construction and post-construction maintenance.

The decision to construct a reservoir somewhere in a given region is frequently taken in response to a community initiative, planned development by a watershed management authority or, more rarely, as a private initiative by water or power companies. Once the initiative for the project is put forth, a design team conducts (1) a preliminary siting study where several alternatives are considered, (2) a feasibility analysis of the preferred alternative, and–if the project is deemed feasible– (3) the necessary design studies. Once the design is completed, the project moves into (4) the construction stage, (5) operation and maintenance throughout its useful life–which ideally encompasses 50 to 100 years–, and (6) closure (which may include removal of the structure and reclamation of the inundation area). A detailed description of the tasks undertaken under each of these subheadings is beyond the scope of this paper; the interested reader is referred to the excellent handbooks edited by USBR (1974) and Golzé (1977). Useful case studies can be found in the monographs edited by Galster, (1989), Burns (1998) and Ferriz and Anderson (2001).

Preliminary siting study

At this early stage of a reservoir project the engineering geologist reviews regional topographic and geologic maps (scales 1:50,000 to 1:100,000), available hydrometeorologic information (e.g., flow hydrographs, precipitation intensity maps), and land use maps to identify potential sites for reservoirs and dams.

From a topographic point of view, the most economical site will usually be where a broad valley in which the stream runs slowly narrows into a steep-sided cross-section. The steeper the sides of the narrowing, the shorter will be the dam. Likewise, the gentler the gradient of the thalweg, the further upstream will the water be impounded, and the larger will be the area of the reservoir for the same height of dam. A good site will also be near the ultimate user of the impounded water (and hopefully upstream so water can be delivered by gravity). At this point it is also necessary to outline the watershed that will contribute water into the reservoir, and to accurately estimate its surface area; this is an easy task where good quality topographic maps are available, but may otherwise require site-specific surveys. The importance of this step cannot be overemphasized; at least one project in central Ethiopia has failed to perform as expected simply because the watershed turned to be 75% smaller than what had been assumed in design.

Since the ultimate goal of a reservoir is to impound water, it is important at this stage to estimate the amount of water that will be available to fill the reservoir. Leaving aside the case of large dams that impound but a fraction of the water conveyed by a major river, for small dams fed by intermittent streams one must be concerned with rainfall distribution patterns and runoff. The best type of catchment from the immediate runoff point of view is one with steep, rocky slopes where the rain, as soon as it falls, runs downhill into a well-defined stream bed in which absorption and evaporation are at a minimum. The worst type is flat country with porous soil where a large proportion of the rainfall sinks to considerable depths and is lost as far as surface runoff is concerned, or where water is held in shallow pools or swamps with a consequent high rate of evaporation. At this time the engineering geologist is only making judicious estimates for comparison purposes, and some simplifying assumptions are adequate. For example, where the stream runs solely during and immediately after the rains, a rough estimate of the water available from a good catchment area is about 25,000 m^3 of water per 1,000 hectares (10 km^2) of the watershed per 10 mm of rain that falls (i.e., 25 percent of precipitation is assumed to end as runoff). In rocky country this figure may be doubled; on porous soils it will be greatly reduced.

At this stage, the engineering geologist is concerned with identifying problematic lithologies (e.g., cavernous limestones or unusually thick channel-fill deposits) (Figure 6), problematic geologic conditions (e.g., active faults or landsliding slopes), and suitable sources of construction materials (e.g., sand and gravel for concrete aggregate, clay for the impermeable core of earth dams, or dimension stone for rip-rap) (Burwell and Moneymaker, 1950). Some of these questions can be answered by consulting published geologic maps and reports, but in all cases the engineering geologist must supplement bibliographic sources with a photogeologic study of each site being considered, and with a reconnaissance survey of the inundation areas and dam sites under consideration. The objective is to compile a reconnaissance geologic map, and to score each site in terms of: (1) Imperviousness of the inundation area (limestones will almost always receive a low score, fractured volcanic and clastic sedimentary rocks will have intermediate scores, and massive igneous intrusive, metamorphic or clastic sedimentary rocks will deserve a high score). (2) Stability of the slopes around the projected inundation area. Mitigation measures, if any appears feasible, must be taken into account when assigning this score. (3) Suitability of the rocks where the dam structure might be constructed, both as foundation and in terms of imperviousness. Recognition of features indicative of active faulting is paramount in this regard. Mitigation measures (e.g., grouting) must be taken into account when assigning this score. (4) Availability of construction materials (in this case the score must take into account volume of material available, accessibility and distance to the source, and a reconnaissance estimate of the quality of the proposed material).

Parallel to the geologic studies, the design team prepares scenarios for different types of dams and conveyance systems, preliminary cost-benefit estimates, and preliminary environmental impact matrices or checklists (e.g., Leopold et al.,1971).

Once all preliminary studies are completed, the team weighs the relative advantages and disadvantages of each site, ranks them in terms of technical suitability, and submits the ranking analysis to the client that commissioned the work. A period of iterative consultation and negotiation is sure to follow, where technical and political issues are melded with the needs of the client, the users, and the community at large. The expectation is that one or two preferred sites will be selected to go on to the feasibility analysis stage.

Figure 6. (a) Dam in northern Ethiopia that lost water at a high rate because of leakage through the cavernous limestones that underlie the reservoir. (b) Detail of the jointed, cavernous limestones that form the substrate of the dam.

Feasibility analysis

Once a specific site is selected as the primary target, the engineering geologist must start documenting the geologic conditions of the watershed, the inundation area, the potential damsite(s), and the borrow areas. The engineering geologist will also collect most of the meteorologic and hydrogeologic data that are needed to determine the feasibility of the project (the first step of which must be to install a gaging station in the feeding stream(s) and one or more precipitation gages throughout the watershed).

At the scale of the watershed, we are concerned with the identification, and suitable mitigation, of potential sources of water quality impairment and potential sources of sediment. The former may include landfills, animal yards, or sewage treatment facilities, to name but a few. The latter may include areas denuded by agricultural activities or fire, alluvial sediments “stored” in the floodplain of the stream, or landsliding slopes, among others. Of course, sediment supply is the ultimate control on the useful lifetime of the project (and hence its economic feasibility), so recognizing these conditions at an early stage is of crucial importance (and may allow for enough time to improve on them).

The substrate and geometry of the watershed will also play an important role in predicting runoff, so the geologist may find it necessary to perform quantitative geomorphologic mapping to divide the watershed in sub-basins, and to determine characteristic parameters for each, such as representative slope gradient, length of overland flow, spacing between channels, extent and type of plant cover, and Manning's roughness coefficients (for both overland and channel flows). Together with a good meteorological model, these parameters can be used to estimate the contribution of each sub-basin to the reservoir (say with a program like the Hydrologic Modeling System of the U.S. Army Corps of Engineers (USACE, 2000)). Ultimately, of course, the success of the project will largely depend on whether enough water will be delivered by the feeding stream(s) to fill the reservoir or not.

Flow discharge records are, unfortunately, scarce. In the most common case the engineering geologist will have to rely on comparisons with other basins, and only rarely will she/he have the luxury of finding a nearby basin–of similar size, topography, orographic setting, and underlying substrate–from which a direct comparison can be drawn. At this point we are concerned about determining the average flow of the stream, but at the design stage we will be concerned with the maximum probable peak flow, so effort spent at this stage in determining flow characteristics will not be wasted. In the best of cases, when gage records are available for a comparable basin, we can use standard statistical techniques to determine average monthly flow, daily peak flow, or variability of total annual flow (e.g., Williams, 1977; USBR, 1974). In the worst of cases the geologist will have to rely on anecdotal reports (always to be suspected, and always needing field corroboration by mapping heights of levees and high-water marks) or in watershed modeling. If the latter, then one must take a close, hard look at precipitation data. Unfortunately the data may be quite meager–the rule, rather than the exception–so it might be necessary to create a synthetic precipitation record (a subject that is beyond the scope of this paper, but the interested reader is referred to the documentation of the HMS (USACE, 2000) and HELP (Schroeder et al., 1994) computer programs). The analysis of precipitation data is discussed further in the discussion on spillways.

As far as the inundation area is concerned, the geologist must at this stage prepare a geologic map at a suitable scale (ranging from 1:5,000 for small reservoirs up to 1:25,000 for large reservoirs) (Figure 7). The objectives are: (1) To identify problematic lithologies (e.g., cavernous limestones), and to assess the feasibility of appropriate mitigation measures (e.g., installation of liners or grouting). (2) To identify faults and swarms of open joints. In the case of the former it is important to look for clues as to whether the fault is active or not–here we use the commonly used assumption that all faults that have had rupture over the last 11,000 years are active. Geomorphologic clues can be used to assess the age of faulting, but the ultimate confirmation would come from seeing the fault cut Holocene overburden soils or alluvium, so it is important to recognize and investigate faults before the overburden soils have been stripped off. The same admonition applies for the dam site itself; in California for example, it is safe to assume that every narrow gorge is fault-controlled. (3) To identify sources of borrow materials within the footprint of the inundation area. Alluvium from the inundation area has been the source of many earthen dams, with the added advantage that the aesthetic impacts caused by removal of this material disappear once the reservoir is filled. (4) Assess the stability of the slopes of the reservoir.

The potential damsite(s) must receive considerable attention at this stage, even though subsurface exploration may be quite limited. Careful surface geologic mapping must be performed, at scales of 1:100 to 1:1,000, and special attention must be given to lithologies, contacts, and possible faults. The latter must be explored for signs of recent activity through shallow trenches. At this point it is also important to establish the depth of alluvial or weathered materials along the thalweg of the canyon, through seismic refraction profiling and one or two exploratory boreholes (if the alluvium is coarse it may be easier to sink a shaft than to drill an exploration borehole). The geologic information thus collected will be used by the design team to assess the feasibility of different types of dams (e.g., concrete arch versus earth dam), and of different alternatives for diversion tunnels, water conveyance structures, spillways, or power houses.

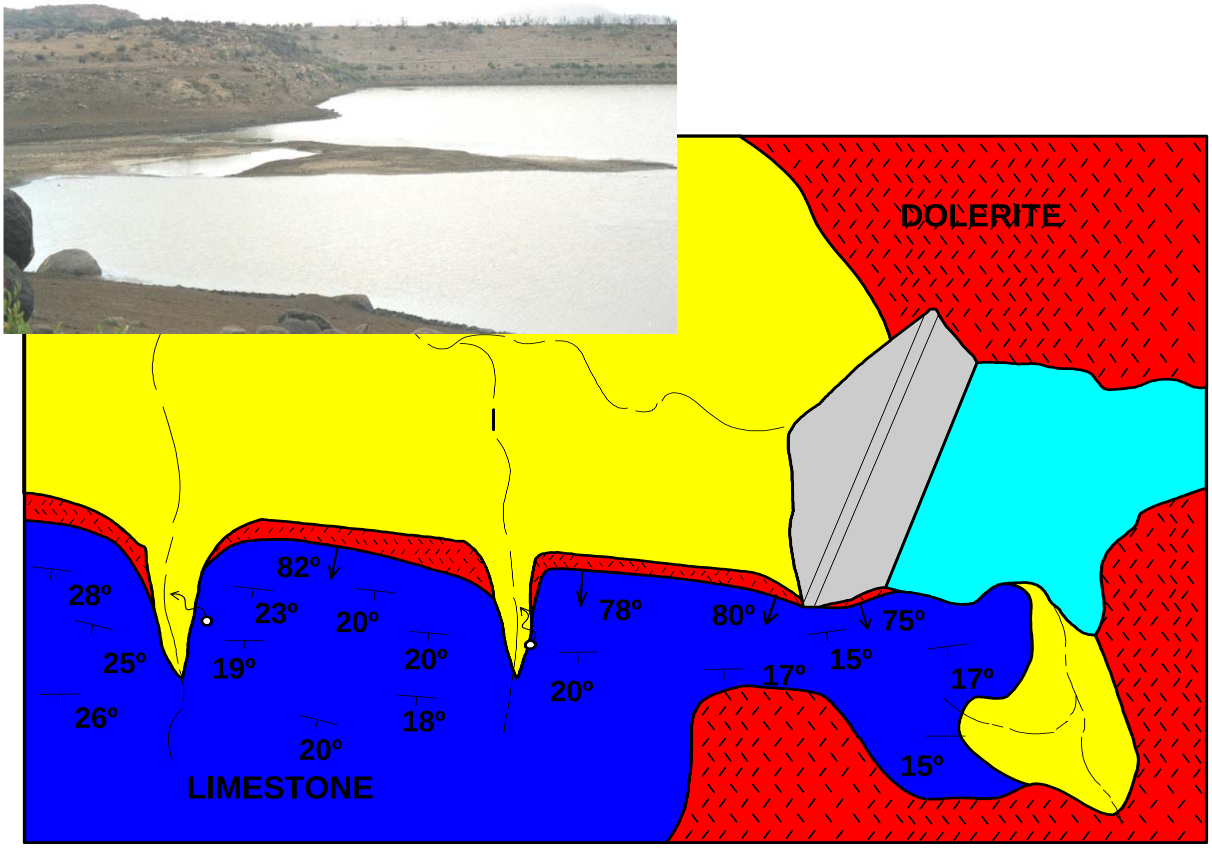

Figure 7. (a) Another dam that has unusually high leakage. The small hill that forms the left abutment is formed by a narrow screen of cavernous limestone. (b) Geologic plan sketch of the dam. The narrow limestone screen is bound by a diorite stock and a diorite dike, so a grout curtain between the two may be the best way to mitigate the leakage problem.

The borrow areas must be mapped and "blocked" at this time (blocking is the process of establishing the volume and quality of different portions of the borrow area). Enough drilling must be performed to establish the depth of the deposits, and enough samples must be collected and sent to the geotechnical laboratory to make sure that the material meets standard specifications. In general we are concerned about grain-size distribution, plasticity, and hydraulic conductivity for soils that are to be used in an earth dam; grain-size distribution, angularity, and mineralogy for concrete aggregates; specific weight, hardness, slaking characteristics, and characteristic size for rip-rap stones; and compressive and shear strength for rocks that will form the abutments of an arch dam (but the strength characteristics of joints and shear zones are more likely to be the controlling factor). Hydraulic conductivity is perhaps the hardest property to estimate accurately, because the low values achieved under controlled laboratory conditions can never be achieved under field construction conditions. It is common to find that as-built hydraulic conductivity is one or two orders of magnitude higher than that determined in laboratory samples.

As before, parallel to the activities of the engineering geologist, other specialists within the design team are preparing cost-benefit scenarios, testing different engineering strategies, and preparing the very important environmental impact assessment. The latter plays a crucial role at this stage, so it deserves at least a brief comment. The stewardship of the environment, and of the ecosystem it supports, is of paramount importance to all nations, and it is our opinion that taking a close, hard look at the environmental impacts that building a reservoir has (and it will always have significant, unavoidable impacts), mitigating those that can be mitigated, and consciously "trading" unavoidable impacts for real societal benefits is an important and responsible task. On the other hand, we caution against the use of the environmental impact assessment process by narrow-interest groups to "kill" beneficial projects.

Design studies

Having demonstrated that the project is feasible, the engineering team shifts its attention to the design of a safe, usable structure. Concrete dams have collapsed suddenly because of bad foundations, improper design, or poor quality materials. Earth dams may not go so suddenly, but once a small breach is started it can widen quickly and empty the reservoir. The most common causes of dam failure are: (1) overtopping (the flowing of water over the top of the dam due to inadequate spillways or to a sudden landslide into the reservoir); (2) undermining, caused by water flowing below the embankment (water flowing through the foundation rocks can lead to piping in granular materials, or slaking and softening of uncemented or weathered rocks); (3) slipping failure of the rocks that form the abutments of an arch dam, or the foundation of a gravity dam; (4) fissures in an earth dam caused by shrinkage, differential settlement, seismic shaking, or by the use of wrongly chosen or badly compacted materials; (5) percolation along tree roots that were not properly cleared before construction; (6) erosion of an earth dam by heavy rains or unusually strong wave action; and (7) piping of granular materials induced by water percolating through an earth dam (piping refers to the formation of "conduits" of concentrated water flow in granular materials; they normally form because the fine particles are flushed out of a granular material that is not properly graded). In addition, a reservoir may not perform as needed if: (8) it does not receive enough water; (9) it leaks too much water through the underlying substrate; or (10) it leaks too much water through the earth embankment itself.

Once the project moves into the design stage, the engineering geologist will: (1) Concentrate on sharpening the level of understanding of the geology of the damsite. (2) Based on this knowledge of the geologic characteristics of the dam site, the engineering geologist will work in concert with other members of the design team to analyze seepage flow through the dam and its foundation, plan foundation improvement measures (e.g., excavation of the foundation materials to suitable levels, compaction of foundation materials, and grouting program), and evaluate static and dynamic stability of the structure. (3) Refine to the best degree possible the understanding of the hydrometeorologic conditions of the watershed, to assist in the design of the spillway(s) and the water intake structures.

In describing their work at the Los Vaqueros dam, in California, Simpson and Schmoll (2001) stated that one of the primary responsibilities of the engineering geologists was to assess the suitability of the foundation rock for each of the various structures at the site (including the core of the earth dam, the concrete cutoff excavation beneath the core, the upstream and downstream embankments, the spillway, inlet structure, inlet/outlet tunnel, and outlet structure) recording significant features on foundation geologic maps at scales from 1:100 to 1:250. Schlotfeld and Van Schalkwyk (1996) have presented a very detailed description of the methods used in the geologic mapping of a damsite. The foundation maps must include details of the bedrock lithology, geologic contacts and bedding orientations, joints, shears, seeps and springs, as well as the limits of the foundation excavation.

The geologic map must be complemented by a good number of detailed geologic cross sections, carefully controlled by a good number of rock cores recovered through diamond-core drilling, and test pits and shafts. Hydraulic-pressure testing of small-diameter boreholes furnishes useful information on leakage conditions and is generally included in the exploration program. The borehole information is generally complemented with seismic refraction surveys, since P- and S-wave velocities are directly related to the physical properties of the underlying soils and rocks. The detailed geologic cross sections are used by the geologist to develop foundation excavation objectives, and a suitable grouting program.

To determine the depth of excavation needed to achieve an adequate foundation for a dam, observation of site conditions in borings and test pits, field testing of soil and rock, laboratory testing of representative samples, and design analysis are needed. Even at well-explored sites, however, the depth to adequate foundation materials is known with certainty only at the locations where exploration was actually performed. To assist construction engineering staff, the engineering geologist must identify a foundation excavation objective; that is, a description of geologic or geotechnical conditions recognizable in the excavation that meet foundation performance requirements. Fraser (2001) has described the following typical foundation excavation objectives:

- Attain a specific geologic unit. For example, "extend the cutoff trench excavation completely through the alluvium and three feet into the underlying granitic rock". This approach requires that sufficient exploration has been performed to identify a continuous geologic unit judged to possess adequate properties for the foundation.

- Excavate to a grade based on field testing results. Examples are the quantitative statements "excavate the shell foundation to an elevation that encounters dense silty sand with an N value of 30 blows per foot as determined by the standard penetration test", and "excavate the cutoff trench to an elevation that encounters crystalline rock with a permeability of less than 10 lugeons". Field testing could include standard penetration tests, water injection tests, and seismic velocity measurements.

- Attain a specific rock quality. For example, "Excavate the dam foundation to slightly weathered granitic rock." Qualities of rock that are potentially significant to dam construction include degree of rock weathering, and the density, orientation, and aperture of joints.

- Achieve a surface that meets a construction control test. For example, “excavate to a surface with an in-place dry density of 120 pounds per cubic foot". It requires an ability to physically test the foundation materials during construction, and a belief that materials with adequate properties will underlie the chosen surface.

- Excavate to a depth indicated by design analysis. This approach is often used when exploration indicates there is no expectation of material improvement within conventional excavation depth. The adequacy of the foundation is based on engineering analysis in conjunction with design solutions that mitigate the impact of the undesirable foundation materials. A common application of this approach is for low dams on weak alluvial foundations, where the foundation is taken to a specific depth, for example, a depth equal to twice the height of the dam.

- Achieve a material judged adequate based on visual observation, as stated by the all-too-common specification "excavate to a depth directed by the engineer". This approach requires the ability to make observations and judgments of strength and permeability during construction, which often can only be done consistently by an experienced engineering geologist.

The selection of the most appropriate approach or approaches is based largely on site geology, the amount of available geologic and geotechnical information, and the performance requirements of the foundation.

Pressure grouting involves the injection under pressure of a liquid or suspension into the voids (primary pores, secondary dissolution cavities, or open fractures) of a soil or rock mass, for the purposes of improving its strength and reducing its hydraulic conductivity. The injected grout must eventually form either a gel or solid within the treated voids, or deposit the suspended solids in these voids. The size of the voids, or the aperture and frequency of the fractures, determines what type of grout is used (e.g., thin concrete slurry, ultra-fine cement, asphalt, or chemical gel), the grouting pressure, and the spacing between grouting boreholes. For example, a rock mass with several long, open fractures might be best grouted with a concrete slurry injected at low pressure, whereas an alluvial gravel may be best handled with an ultra-fine cement injected at intermediate pressure. Grouting is normally performed in several stages. For example, the first group of grout holes might be drilled on a 10 m spacing. A second group is then drilled and sampled at the mid points between the first holes; the samples are used to estimate the extent to which the previous round of grouting was successful, and the grouting parameters are adjusted as needed. Sometimes as much as five rounds of grouting are needed before the objectives of the program are achieved. The engineering manual prepared by USACE (1984) is an excellent reference on the subject of grouting.

Water continuously move through a damsite. If a concrete dam, then most of the seepage takes place along the foundation rocks, but in the case of earth dams water seepage through the embankment is a natural, expected phenomenon. This expected seepage is normally handled by building soil filters and drains into the structure of the dam, and in order to design them a thorough seepage analysis must be conducted. The methods of analysis are complex, and require quite a bit of experience, but they have been clearly described by Cedergren (1997), who provides many examples of flow nets for many dams.

The stability analysis of an earth embankment normally involves calculation of the static driving forces (and/or momentums) and the static resisting forces (and/or momentums). Their ratio determines the factor of safety (a stable embankment has a ratio, or factor of safety, equal to or greater than 1.0). Most analytical procedures (see Duncan, 1996a, 1996b for useful summaries) divide the mass above the potential failure that is being considered in "slices", and consider the forces that act on each slice. The requirements of force and momentum equilibrium are then applied to the individual slices, with the factor of safety against a slope failure then being defined as the ratio of the maximum shear strength along the trial slippage plane to the shearing resistance at equilibrium. A pseudo-static analysis is carried out in the same way, but an additional, hypothetical force is allowed to act laterally on each of the slices. Using the pseudo-static approach described above, one can estimate by trial-and-error the acceleration induced by a lateral force large enough to result in a theoretical factor of safety of 1.0. This acceleration is referred to as the yield acceleration.

Once the yield acceleration of the slide block has been determined, permanent displacement can be calculated by double numerical integration of those parts of a strong-motion acceleration record that lie above the yield acceleration (the acceleration record must be first scaled to take into account magnitude of the design earthquake, attenuation between the earthquake source and the site, the nature of the substrate, and the height of the embankment). The calculation is based in the procedure initially proposed by Newmark (1965): Newmark's method models a failing slope as a rigid-plastic friction block that has a discrete yield acceleration (the acceleration required to overcome frictional resistance and initiate sliding on an inclined plane). The analysis consists of double integration of those “peaks” of the acceleration record that are above the yield acceleration. The first step of integration results in an estimate of the downhill velocity of the sliding block, and the second step of integration lets us calculate the cumulative downhill displacement of the block. In general, a well compacted dam embankment can accommodate as much as 30 cm of displacement without failing.

Foundation analysis of appurtenances

Appurtenances of a reservoir include spillways, water intake structures, water outlets, penstocks (i.e., pipes to convey water to power-generating turbines), coffer dams and tunnels to divert river flow during construction, and secondary dams. Some of them require the same type of studies required for the main dam, so they need not be repeated here. Others, like spillways and penstocks, are unique in their function and so require special hydrologic, foundation, and vibration analysis. For the sake of brevity we concentrate on the latter in this section.

The spillway is probably the most important of the appurtenances of a dam. It provides three important functions: (1) It prevents overtopping of the dam, which in earth dams could lead to catastrophic failure of the structure. (2) It limits the elevation of the reservoir to avoid flood damage along the shores of the reservoir. (3) Supplements the water outlets in their flood control functions.

Because of these important functions, the spillway has to be carefully engineered to accommodate the “maximum probable peak flow” (or the dam has to be designed to be able to withstand overflow without catastrophic failure), and stand the vibration and erosion associated with the turbulent flow of flood water. The “maximum probable peak flow” is a matter of engineering judgement (common sense should make it clear that it cannot be less than the maximum historical peak flood), but it is common practice to estimate it based on the assumption that it would happen when a 100-year, 24-hour storm (hereafter called the design storm) occurs at a time when the reservoir is filled to capacity (see USDA, 1985, for further guidance). There are several hydro-meteorologic techniques that can be used to determine the design storm hyetograph (i.e., a time versus depth of precipitation histogram) (Feldman, 2000; Levy and McCuen, 1999; Pilgrim and Cordery, 1975; USDA, 1986), but many developing countries may not have the extensive network of gages needed, nor the necessary historic coverage. Where only point rainfall records are available, one can use the method of statistical maximization described by Hershfield (1965) to estimate the total 24-hour precipitation, and conservative assumptions regarding the skeweness and kurtosis of the hyetograph (e.g., Hromadka, 1986). If the drainage basin is large, or if orographic effects have a pronounced effect in the intensity of rainfall throughout the basin, then it is necessary to divide it in sub-basins, and estimate design storm hyetographs for each of the sub-basins.

Once the design storm hyetograph has been constructed (and we cannot stress enough the fact that this is probably the most important step), then one performs a routing analysis to calculate the way in which excess rainfall would move through the basin as runoff. The routing analysis is far from trivial, and includes estimation of short term “losses” applicable to the design storm (e.g., infiltration, depression storage), deduction of such losses from the storm hyetograph to determine volume of rainfall excess available for runoff, actual movement of runoff as overland flow and through the network of channels (which in turn is a function of slope gradients, soil types, density and type of plant cover, and hydraulic characteristics of the channels), and gains from base flow. This type of routing analysis can be performed using standard hydrologic methods (e.g., Bedient and Huber, 1988), or by using integrated computer programs, such as the Hydrologic Modeling System of the U.S. Army Corps of Engineers (USACE, 2000) and the SITES program (USDA, 2001). The ultimate goal is to determine inflow hydrographs to the reservoir; this may include hydrographs for all major tributaries, an “average” hydrograph for small sub-basins that drain directly into the reservoir, and a “hydrograph” to account for direct precipitation in the inundation area itself. The different inflow hydrographs will very likely reach their peaks at different times, so their algebraic addition results in a complex compound inflow hydrograph (which for all but very large reservoirs can be assumed to be the same as the outflow hydrograph through the spillway).

Once the outflow hydrograph has been estimated, several spillway designs and lengths are evaluated, in term of their hydraulic efficiency, stability, and cost. Spillways may have gates that can be lowered to increase their discharge (more expensive and liable to malfunctions, but more flexible to make maximum use of available storage and head), or have a fixed uncontrolled crest in which discharge increases geometrically as a function of head above the crest (less expensive in terms of both construction and operation). Cost and performance are also affected by the type of conveyance structure used: (1) Concrete chutes or shaft (morning glory) spillways are more expensive and sensitive to foundation conditions, but they are more predictable in terms of their hydraulic behavior (which in turn makes it easier to design energy dissipation structures). Particular care must be given to avoid toe erosion at the discharge end of the structure, which could cause caving of the foundation materials and downhill sliding of the whole structure. Vibration induced by the turbulent flow of water could also trigger liquefaction of soil foundations, so a standard liquefaction study (e.g., Youd et al, 2001) must be part of the design process. (2) “Natural” overflow channels, where the channel is excavated in the natural substrate and is not lined with concrete, are less expensive and not as sensitive to foundation failure, but they are susceptible to erosion damage and are somehow unpredictable regarding down-channel impacts. In general, it is best to excavate the spillway channel down to bedrock, but if this is not possible it may be possible to stabilize the channel through engineering of the channel section, channel slope, and channel vegetation cover (the SITES software was developed to assist in the design of earthen channels; USDA, 2001).

The discussion on spillways serves to illustrate the need for peer review of all design activities, be it the exploration program, the grouting plan, the design of the dam itself, the seepage and stability analyses, or the design of appurtenant structures. We strongly recommend establishing a dam safety review panel at federal or state level, so that individual design teams can benefit from the peer review process.

On-site professional support during construction and post-construction maintenance

To conclude this section, brief mention must be made of the important role that engineering geologists play during construction and post-construction operation and maintenance. Simpson and Schmoll (2001) have listed as important activities (i) the on-going assessment of foundation rocks exposed by the excavation; (ii) confirmation that the design intent described in the foundation excavation objectives is met, and (iii) controlling the quality of the grouting program. For example, during construction of the Los Vaqueros dam, in California, the geologist's presence was required to determine the most appropriate way to modify the excavation to address conditions different than those anticipated during the design. In areas where the weathering criteria were met, but where excessive jointing or shearing made the foundation unacceptable, the geologist directed overexcavation until suitable foundation was exposed. Upon completion of the mass foundation excavation and the foundation grouting operations, the foundation for the core of the dam was required to be shaped "...so that a relatively uniformly varying profile is obtained free of sharp offsets, protruding points, edges, or breaks, and so that variations in elevation are gradual...". Sharp breaks in slope or steps in the foundation were not allowed, to prevent any cracks from forming within the clay core due to differential settlement. Cavities, depressions, and in some instances, steps in the core foundation could also be treated by placing concrete on the foundation. The removal of loose blocks, overhangs, and protrusions was done so that adequate compaction of the core material against the foundation could be achieved and so that no void spaces would be created at the core - foundation contact. It was the engineering geologist's responsibility to delineate areas requiring shaping.

In some instances the engineering geologist may be called after the reservoir has been in operation for several years, to diagnose the reason for larger-than-expected leaks, sudden increases in the turbidity or discharge of down-gradient springs, or the development of fissures in the embankment. Every case is likely to be different, but at the end the question will be what to do to solve the problem. Leakage through the basin is probably the toughest problem to deal with, but in small reservoirs might be amenable to installation of a clay or synthetic liner. Leakage through thin screens of limestones or brecciated volcanic rocks, or through channel gravels under the embankment, may be mitigated through grouting (Figure 10b). In all cases, however, the first step toward a solution will be careful documentation of the problem (for example, the maintenance team must resist the temptation to grade over fissures before the geologist has a chance of mapping their distribution in detail).

Groundwater

Groundwater exploration

Groundwater is a wonderful resource, in that it is present almost anywhere in the world. Finding it at an accessible depth, and in an aquifer that has adequate hydraulic conductivity and storage volume is another thing. The best targets are, by far, alluvial aquifers. In Ethiopia these types of aquifers are found in fault-bound grabens, such as the Kobo-Girana (Figure 8) and the Kombolcha valleys (to name but two that are traversed by the main route between Addis Ababa and the northern city of Mekele) (Chernet, 1988). Limestone aquifers are almost as good (Alemayehu, 1993), followed by autobrecciated volcanic rocks. Drilling through these rocks is not as easy, however, so direct exploration is more difficult than in alluvial sediments. Finally, fractured-rock aquifers are unpredictable as far as yield is concerned, but in many areas of the world they support wells that are adequate for rural supply.

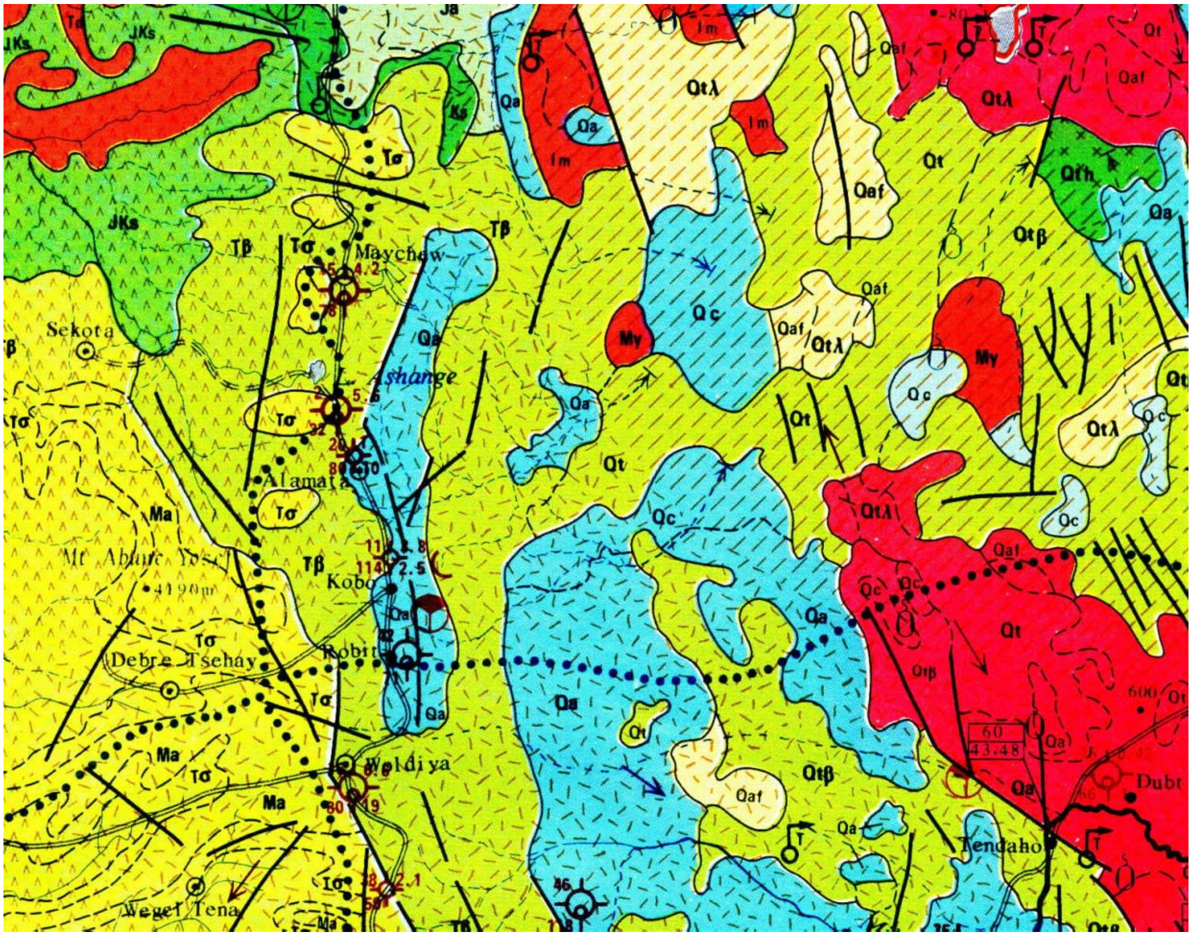

Figure 8. Excerpt from the hydrogeologic map of Ethiopia (Chernet, 1988), showing the location of the Kobo-Girana basin (the elongated graben immediately to the left of the center of the figure). The basin is about 100 km in length and 10 km wide, and the town of Kobo is in its southern portion.

Alluvial aquifers

Finding groundwater in basins such as the Kobo-Girana and the Kombolcha valleys is not the problem. Just dig and you will eventually find it. The real challenge faced by the exploration hydrogeologist is to site and design high yield wells. An ideal rural well would be less than 50 meters deep, would be screened in the lower 15 meters (20-cm diameter), and would have a safe yield of about 300 liters per minute. In contrast, an agricultural well equipped with an electric pump would need to have a safe yield of at least 1,000 liters per minute to service an orchard area of 100 hectares. A farmer’s dream would be a well that is no more than 150 meters deep, and is screened in the lower 50 meters (40-cm diameter).

How do we go about finding this dream well? The prime exploration strategy in developed basins is careful surveys of existing wells. In contrast, vertical resistivity soundings remain the prime exploration tool in areas where neighboring wells are scarce, but the method cannot discriminate between low-yield and high-yield horizons. Finally, seismic refraction surveys are sometimes useful to locate the depth to the water table, because water has a distinctive compressive wave velocity of about 1,525 m/sec. Ultimately, however, at least one pilot hole has to be drilled and carefully logged to characterize local aquifer conditions.

Fractured-rock aquifers

Prime exploration strategies when dealing with fractured-rock aquifers are lineament studies, surface fracture surveys (for both orientation and spacing of the fractures), surface geophysics, and drilling.

The detailed analysis of surface fractures is of crucial importance for pinpointing and characterizing zones of intense fracturing. Data must be collected, in a systematic way, about the orientation of each fracture, the spacing between fractures, and characteristics such as openness, mineral fill, or annealing. The interpretation of structural orientations requires the use of stereographic projections to represent and analyze the three-dimensional data in two dimensions. Fractures and other discontinuities (e.g., dikes or veins) are plotted in the pole format in order to detect the presence of preferred orientations, thus defining discontinuity sets, and to determine mean values for the orientations of these sets. This process can be facilitated by contouring to accentuate and distinguish the repetitive features from the random features. We believe that careful analysis of structural data eventually leads to the recognition of fracture directions that make “good geologic sense”, in that they can be reconciled with the tectonic stress regime of the region. It is these regional fracture sets that we normally look for in an exploration program.

Spacing between discontinuities, and patterns of spatial distribution, can be characterized through the use of standard statistical techniques (e.g., Swan and Sandilands, 1995). For example, spacing between fractures can be easily represented, and visualized, by simple frequency histograms. Modal spacings of less than 1 foot are often indicative of a zone of intense fracturing.

Surface geophysics can be of some assistance in locating fracture clusters with high hydraulic conductivity, but it can hardly be considered a sure-fire method. The most promising approach is the so-called VLF method (very low frequency electromagnetic surveying). The VLF method relies on the fact that some coastal nations operate long wavelength, or very low frequency, radio stations for communication with submarines. The electromagnetic emissions from the VLF antennas propagate as air, water, and groundwaves, with magnetic and electric field components. Far away from the transmitter, the VLF field can be regarded as a uniform electromagnetic field that is oriented parallel to the surface of the ground and perpendicular to the bearing of the transmitter. In the ground, the primary (source) field propagates vertically away from the transmitter. Upon encountering an electrical conductor (e.g., a fluid-filled fracture), the propagation of the source field causes the flow of secondary electrical currents, which in turn generate a secondary magnetic field that adds its strength to the total magnetic field. In the presence of a lateral change in conductivity, the secondary field is shifted in phase relative to the primary field. To the extent that the observed VLF anomalies are caused by relatively vertical and narrow structures elongated parallel to the bearing to the transmitter, the interpretation of the data is straightforward: the surface trace of the structure is inferred to be where there is a positive anomaly in the total magnetic field and where the in-phase response changes sign (the crossover point). Interpretation is complicated, however, by non-geologic conditions (e.g., power lines or grounded metal fences), topography, or departures from the ideal assumption that the conductor is narrow, steeply dipping, and parallel to the bearing to the transmitter.

Ultimately, the exploration program has to be put to the test by drilling. We have identified a lineament that coincides with a cluster of fractures, the fractures appear to have formed in response to a large scale tectonic stress regime, and surface geophysics suggests that a vertical, narrow conductive zone can be found at depth. Hence, we advise the property owner that it is time to retain a driller, and our client reasonably asks “How deep should we drill?” We feel inclined to abandon a hole that is more than a few hundred feet in favor of a new location. Chasing fractures can be an extremely costly proposition, as witnessed by many “dusters” drilled to depths of two or three thousand feet. Page et al. (1984) reached a similar conclusion after analyzing more than 200 well records from the metamorphic rocks of the Sierra Nevada of California. They found that most producing wells had depths of less than 180 feet, with yields commonly in the range between 5 and 60 gpm. In contrast, wells that had been advanced more than 215 feet in search of a producing fracture had yields that were often less than 5 gpm. In a separate study, Davis and Turk (1964) compiled the yields of a different set of 239 wells in intrusive rocks of the Sierra Nevada, and found that the median flow for wells with a depth of less than 100 feet was 10 gpm or more, but less than that in wells that had been advanced more than 200 feet. We stress the fact that these are empirical observations, to which no doubt many exceptions can be found. After all, fluid-filled fractures can remain open under lithostatic loads of tens of thousands of feet. If only we had the budget to keep looking for them!

Groundwater extraction through wells

Wells are the traditional way to extract groundwater, and accordingly there is a large variety of techniques to construct them. Where the water table is not very deep (< 10 m), large-diameter hand-dug wells are a feasible alternative. More commonly, however, wells are drilled using a drilling bit suspended from a steel cable or a pipe stem (Driscoll, 1989, is the standard reference on well drilling). When drilling through unconsolidated sediments one has the option of using hand-driven augers, or truck-mounted augers. In consolidated rocks one can use truck-mounted rotary drilling, diamond-core drilling, or percussion drilling. Most truck-mounted methods are expensive, and there are but a few drilling rigs in most developing countries. One low-cost, relatively low-technology option is percussion drilling using tools suspended on a steel cable (the so-called cable tool method). The necessary equipment is a tripod, a cat head (a rotating drum operated by a small gasoline engine), a 16 mm steel cable (or a stout rope), and a suitable set of percussion tools

(Figure 9). The heavy string of drilling tools is lifted with the cat head, and then is allowed to free fall against the bottom of the hole. The drill bit crushes the rock, and the reciprocating action of the tools mixes the crushed particles with added water to form a slurry at the bottom of the borehole, which is removed with a bailer from time to time. The cable tool method has the significant advantage that all equipment and tools can be manufactured locally, with minimal reliance on imported equipment. It has the disadvantage that drilling progress is slow (anywhere from 1 to 5 meters per day in most cases), but this is only a relative "annoyance" when dealing with typical rural wells, which are typically less than 50 meter deep.

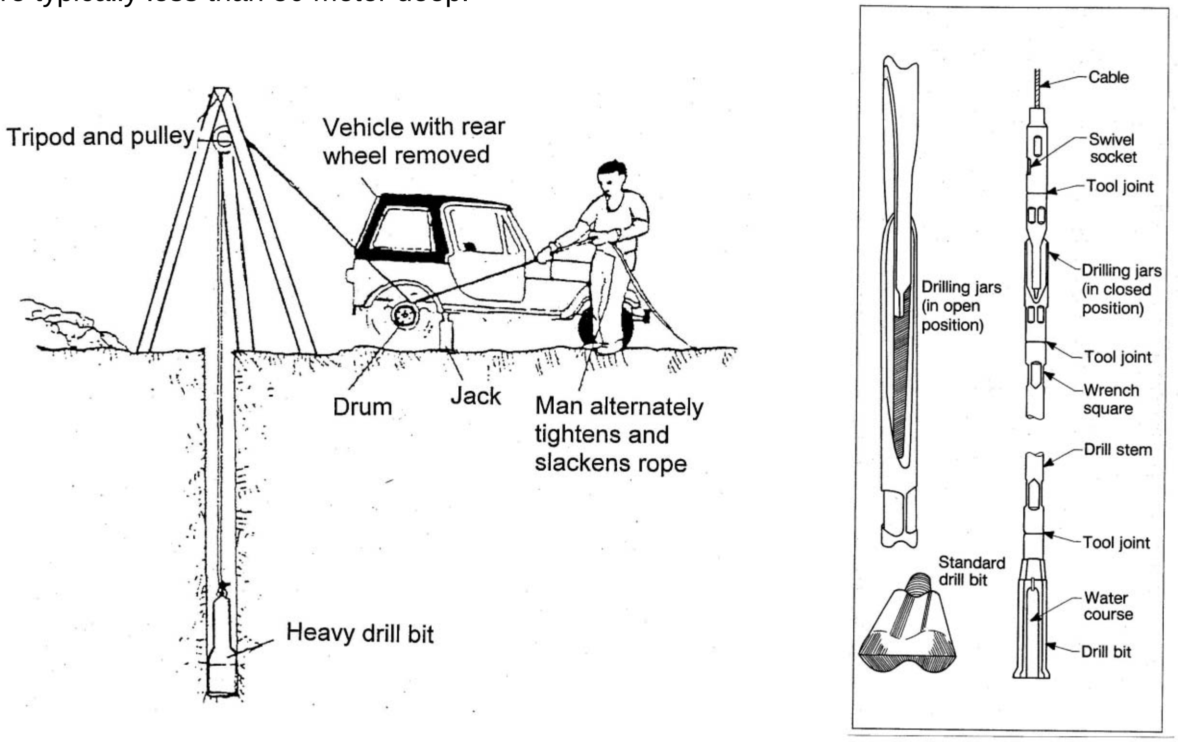

Figure 9. (a) A simple but very serviceable arrangement for cable tool drilling. (b) Typical set of percussion tools used in cable tool drilling (from Driscoll, 1986). A full string consists of five components: drill bit, drill stem (to give additional weight to the bit), drilling jars (when the bit gets stuck it is freed by upward blows of the free-sliding jars), swivel socket, and cable. The length of the whole assemblage helps maintain a straight hole when drilling in hard rock.

Once the drilling is completed, the actual well must be constructed. The steps include: (1) Lowering of the screen and blank well casing. PVC pipe is a convenient, durable material with which to construct the screen and casing. If machined screen is not available in the country, a screen can be manufactured in place by cutting slots in blank pipe with a thin saw. The inside diameter of the screen and casing must be no less than 10 cm, to accommodate a downhole pump or a pumping cylinder. (2) Laying down the granular sand pack. The annulus between the borehole and the casing is filled with a medium- to coarse-sand, up to a meter above the top of the screen. The objective of the sand pack is to facilitate the movement of water from the formation into the screen, while filtering fine sand and silt from the formation (the grain-size distribution of the sand pack must be selected based on the grain-size of the formation, as described by Cedergen, 1997). The sand pack must be poured in slowly using a tremie pipe, and tamped from time to time, to avoid bridging and the consequent formation of cavities. (3) Installation of the sanitary clay seal. To avoid infiltration of surface water into the aquifer through the borehole, a sanitary seal of expansive clay must be placed to a depth of 1 meter above the sand pack. The clay can be mixed in the surface to form a thick slurry, and then poured into the annulus of the well, or it can be poured in the annulus as dry chips and then hydrated in place. (4) Backfill of the annulus up to the surface and surface completion. After a few hours, once the sanitary seal has had a chance to cure, the annulus around the casing is backfilled with native soils or concrete, and a concrete pad is constructed at the surface. Imbedded on this pad are the necessary bolts to anchor the pump on top of the well. (5) The last step in well construction is well development, which is the name given to alternately rising and lowering a plunger inside the well to induce back and forth flow of water through the formation and the sand pack. Water is bailed out of the well from time to time, until the initial turbidity disappears.

The selection of a suitable pump depends on many factors, among which are availability of electric power, reliability of gasoline or diesel supply, availability of a given type of pump or spare parts in the country, and pumping needs. Details can be found in Driscoll (1986) and need not be discussed here. We would like to point out, however, that simple piston (reciprocating) pumps powered by a wind mill–or even by hand when the need arises–are a straightforward alternative with almost universal application. Besides, a simple piston pump can be built locally, with minimum reliance on imported equipment, and can be easily maintained by the local mechanic.

Groundwater extraction through galleries

As mentioned earlier, the Tertiary flood basalts appear to host significant groundwater resources. Most basalt flows have good vertical hydraulic conductivity due to columnar jointing, and the autobrecciated bases and tops of the lava flows have enough porosity to hold significant volumes of water. Excavation of horizontal galleries (in essence horizontal wells) along the brecciated intervals is a viable way for tapping these aquifers. Driving galleries is not trivial, but the rubbly contacts between lava flows are not as hard as the flow interiors, water collected in galleries can be distributed by gravity (hence bypassing the need for pumps and the energy needed to run them), and there is enough mining going on in the country that there is a small number of miners that could be trained to be crew leaders.

Galleries are used in Mexico, Haiti, and the Canary Islands for water production. The typical gallery is 1.5 to 2 meters in diameter (just what is needed for the miners and their equipment to get through), less than 100 m long, and are gently inclined toward the portal.

They are cut through traditional drill and blast tunneling techniques (USACE (1997) provides useful information regarding the details of a drill and blast operation).

A gallery can yield thousands of liters per minute, and this water can be conveyed by simple gravity flow (a good portion of the city of Port Au Prince, capital of Haiti, receives its water in this way). However, the gallery must be protected against entry by animals with a stout, hermetic door (excluding daylight helps avoid growth of algae), and the water may need to be chlorinated for potable use.

5. LOCAL MANAGEMENT OF WATER RESOURCES

The previous discussions highlight the fact that the development of water resources is a complex task that requires effort, ingenuity, and commitment. Furthermore, water works have to be maintained, enlarged and improved as they continue to serve a growing population. This requires personnel, money and time, which is why it is crucial that any water development project has the support of its users.

A system that works well centers on the establishment of water districts. A water district is owned by the users, and overseen by an elected board. The board in turn hires the necessary technical and administrative personnel. The technical staff worries about the construction of water works, and the delivery of water to the individual users. The administrative personnel, in turn, worries about billing the users for the services rendered, and uses the profits to finance maintenance and new facilities.

The initial endowment is the cornerstone of a water district. In the case of one irrigation district in California, the initial endowment was secured through a low-interest private loan secured by the land of the private property owners. In another case the state did the initial construction of the water works, and then “sold” it to the user community on a 30-year payment schedule.

Private or community-owned water districts may need to be coordinated by a watershed water authority. The role of this authority is to coordinate the development of water works that are used by several water districts, to protect the water use rights of downstream users, and to undertake tasks that are beyond the scope of individual water districts (e.g., scientific research or environmental protection measures at the scale of the watershed). A watershed authority may be a state agency, but it can also be a private entity, formed by the water districts that operate in that watershed.

We are convinced that water districts and water authorities are one of the best ways to manage water resources. They also foster the economy of an area by employing local technicians, and bidding contracts to engineers and contractors. Finally, because they are community owned, they foster protection of local water works, payment of fees, and overall use and maintenance of the system.

Public agencies certainly play an important role in the development of water resources. For one thing, it is through them that initial funding can generally be secured. For example, in Ethiopia the federal government and the World Bank have jointly created the Ethiopian

Social Rehabilitation and Development Fund (ESRDF). This organization has simple, straightforward funding protocols, and can quickly funnel World Bank funds unto projects that have a high potential in assisting to the social rehabilitation, poverty alleviation, and development of Ethiopia. ESRDF has promoters that “advertise” its functions throughout the country, and is always ready to receive community initiatives for socially significant projects (e.g., rural water supply, irrigation, food production, education, or public health to name but a few). The rules of the game require that the requesting community contribute a portion of the cost of the project (10 to 25%), either financially or in labor. If a project is approved, the World Bank provides the necessary funds, and ESRDF provides technical support and project oversight. The project then goes to open bid, both for design and for construction, which gives local companies the opportunity to participate. Once the project is completed, ESRDF turns it in to the community, who from there on takes charge of its operation and maintenance. In our opinion, the ESRDF model has proved very successful; other developing countries may be able to emulate it to great advantage.

EPILOGUE

We expected this paper to be a brief summary of water development strategies, but one thing led to another, and the brief summary has developed into a full-length manuscript. We wrote it with young engineering geologists in mind, and hope they will find in it enough ideas and bibliographic references to tackle their first assignments successfully. Ultimately, we will all gain as more of our young geologists and engineers join the battle to provide water for the world. Here is to a tough, exciting challenge!

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