Engineering and Environmental Problems in Reservoirs Constructed in Karst Terrain
Case Study: The Three Gorges Dam, China

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ABSTRACT

The goal of the thesis was to explore the issues associated with construction in karst terrain. The characteristic geology and features of karst terrain were explained. The mechanisms of surface and underground flow in karst were detailed. Special attention was paid to the exchange of surface and underground water.

The accelerated transport of contaminants through karst terrain was described. Problems characteristic of foundation and tunnel construction in karst areas were laid out. Current solutions were given. The problem of reservoir construction in karst terrain was paid special attention. The change in regional flow was emphasized; current standard practice for karst reservoir formation was described. A case study with a ninety-year study window was described.

A case study of a dam currently under construction in karst terrain, the Three Gorges Dam in China, was given. Reasons for the site selection and complications associated with it were detailed. The problem of regional flow changes was given special attention. The change in hydraulic head due to the filled reservoir was calculated, and areas of potential increased surface flow were identified.

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I. Introduction

As the world's population rises, construction projects are more frequently being undertaken on karst terrain. Builders have avoided these areas of complex geology for years, so the amount of information and standard practice in this area is scant. Below, some of the current problems preventing the full use and land and water resources in karst terrain will be described. Current and projected solutions will also be examined.

II. Karst Hydrogeology

2.1 Characteristic Features and Geology

2.1.1 Karst Lithology

Soluble, usually carbonate, rocks at or near the surface characterize karst terrain. A carbonate rocks is defined as having greater than fifty percent carbonate minerals by volume. With rare exceptions, carbonate rocks contain insoluble mineral particles. Limestone, chalk, dolomite, gypsum, and salt are often constituents. The process of karstification, by which characteristic features are formed, is caused by the physical and chemical action of fluid on rocks. Finer grained rocks tend to be more soluble. Surface relief is characteristic. A surface and ground water network is made up of water circulation and action in joints, fractures, cracks, and other features. The top of the karst region may be bare or covered by a layer of soil.

2.1.2 Surface Features

Several surface systems indicate karst terrain. Poljes are gentle depressions, usually elliptical, in the topography. They slope, slightly, connecting the spring (discharge) and the swallow-hole (recharge) zones. They may cover areas from one-half to five hundred square kilometers. Typically poljes are associated with permanent or seasonal springs, almost always aligned along the longer axis. Any surface stream or river flow also tends to follow the long axis. The axes often correspond to tectonic features. Poljes are very rare in Asia. Underground joints, caves, shafts, or channels usually accompany poljes. Flooding is common in these areas, as the outlets have poor capacity. The inlets are often high capacity. These often take the form of karren, which are small and usually steep depressions. These depressions tend to occur in groups and are separated by small, steep ridge systems. Karren form in surface carbonate, gypsum, and salt rocks. They tend to form near poljes, usually along the longer axis. The presence of cracked limestone encourages their formation. Karren can be spaced by several centimeters to several meters. Typically, their depth is between two and eight meters. Dolines, or sinkholes, are cone-like, hollow depressions. Their diameters typically range from two meters to one hundred meters. They may extend to depths of one kilometer. Dolines are formed by the collapse of channel and cavern floors. They usually occur in groups and are associated with faults. Dolines are usually placed above the water table, but may be flooded. These features are of special interest because they can form in a matter of hours, causing great destruction. Dry valleys, elongated recesses, occur when karst groundwater flow conditions are so favorable that surface flow tends not to form. Typically, they are located over dolines and underground features such as jamas and caves. These features provide a very high hydraulic conductivity, creating favorable groundwater flow conditions and diverting surface flow. Groundwater flow in dry valleys exists primarily as open stream flows in conduits and caves; pore flow is negligible in comparison. The underground streamflows may be in the vadose or fully saturated zone. Open surface streamflows rarely occur in these areas; those present are seasonal. The water table in these valleys tends to be very low, even in flood times.[1]

2.1.3 Underground Features

Underground features not only identify karst terrain but also are responsible for much of the groundwater flow. Jamas, or shafts, are zones of vertical circulation, often filled with air. They are sometimes saturated only during the rainy season. Jamas are formed by water action within the vadose zone, and thus tend to be approximately circular. They are important joint systems, which form part of the surface water/ground water interface. Jamas provide rapid transport through the vadose zone, often acting as swallow holes. Their depth corresponds to the water table; they usually do not come close to confining or retarding layers. The tops are always located within the vadose zone, but jamas may extend far into the saturated zone. Jamas of up to five hundred meters in depth have been found. Channels are horizontal or gently sloping, and provide mainly lateral circulation. Their shape and dimensions are highly variable; high flow conduits tend to be fairly rectangular. Their flow is often provided directly by jamas. They may have dimensions of one centimeter to ten meters. Channels, also called conduits, are formed when solution widens fractures in carbonate rocks. Channels often empty into a lake or ocean, or they may directly feed small springs. Caves are essentially widened channels. Sometimes, when close to the surface, they provide a direct surface/ground water interface, often feeding small springs. They may have lengths of up to five hundred kilometers. Caves seldom act as swallow holes.[1]

2.2 Porosity and Groundwater Flow

2.2.1 Genesis and Characteristics of Porosity

There are three types of porosity in karst aquifers: primary, fracture, and conduit. Primary porosity occurs through intergranular pores, open and filled vugs, and small isolated joints and bedding plane partings. Fracture porosity is facilitated by high concentrations of joints, fractures, and bedding plane partings. These features, though tectonic in origin, may be enlarged later by solution. Conduit porosity occurs in open channels and pipes, which may have widely varying sizes and shapes over the system. Primary porosity is usually isotropic. Fracture porosity is almost always locally anisotropic. However, the mean porosity over a large area may be effectively isotropic. Conduit flow is always and often highly anisotropic. Flow in primary pores is laminar and can be characterized by D'arcy's laws. Fracture flow is laminar, but usually not D'arcian. Conduits usually have turbulent flow.

Highly primary aquifers have a well-defined water table surface. The presence of fracture porosity leads to an irregular water table. Conduits act as subsurface drains, which may follow the water table. They may also carry water over and below the water table. The pore types vary in their response to sudden events, such as flood-level precipitation. Primary pores response slowly, fracture pores moderately, and conduit cavities rapidly.

The primary (granular) porosity in these areas is formed during genesis, sedimentation, and petrification processes. Secondary porosity occurs post-petrification, by the processes of solution or fracturing. The number and size of pores and other open spaces increases with time. Thus, the older a karst area, the larger its porosity and permeability.

Conduits in a karst system tend to make up only a small percentage of the total pore volume, but a majority of the flow. The hydraulic conductivity of these features is very high. Sinking occurs through small joints or in mass through swallow holes. Especially when they are only partially filled, the behavior of fluid in conduits is similar to surface flow.

The mean effective porosity of karst systems is usually between one and two percent. In the strongly cracked upper zone, and in areas of highly advanced karst and tectonic processes, the effective porosity may be as much as ten percent. These areas of high porosity are uncommon, but may be regionally concentrated. The construction of artificial reservoirs in regions containing these areas eliminates the possibility of impermeability.

Porosity in limestones and dolomites tends to be proportional to grain size and heterogeneity. The porosity of micrite is generally less than two percent. Sperite porosity ranges between five and ten percent. When carbonate rock becomes dolomitized, the porosity usually increases by five to fifteen percent. Intact and massive limestone usually has a porosity of less than one percent.

The hydraulic velocity in areas of advanced karst development tends to be very large. In conduits, it typically ranges from 0.01 to 1.21 meters per second. Pore flow tends to be less than 1.97×10^{-3} meters per second.

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Carbonate rocks that initially have a low void density, such as marble and evaporates, tend to develop high conduit permeability over time. Rocks that are initially porous, thinly bedded, or highly jointed still form conduits. However, these tend to be rarer, smaller, and less connected. Early in karst formation, the flow in conduits is usually slow and laminar. However, eventually the conduit meets up with an output feature, usually a spring or other conduit. Soon the flow becomes turbulent. At the time that the flow changes, the diameter of the conduit is typically between five and fifteen millimeters.

Shaley limestones, crystalline dolomites, and highly permeable rocks control diffuse flow. Caves in this region of flow tend to be small, rare, and irregular. In the free flow regime, thick and massive soluble rocks are present. The caves form a highly integrated conduit system. There are three types of free flow: perched, open, and capped. An impervious layer, near or above the baseline flow, underlies perched flow. The cave streams are perched, and often partially air-filled. In open flow, a layer of soluble rocks extends up to a level surface. The caves tend to be short and connected, taking their input from sinkholes and carrying heavy sediment loads. In capped flow, the aquifer is confined and often pressurized by an impervious rock layer. The caves tend to be long and well integrated, fed by vertical shafts. Flow beneath the cap is largely lateral. In deep flow, the karst region is located far below the baseline flow. Flow occurs in submerged and normally saturated conduits. Deep flow may be either open or capped. Caves in the open regime are short, cylindrical, and often choked with sediment. Capped flow encourages a long conduit system under the caprock. Flow tends to be very active and fully saturated. Confined aquifers are controlled by structural or stratigraphic barriers. Confined flow may be under artesian or sandwich conditions. Artesian regimes contain impervious beds, leading to flow below the regional baseline. A vertical and lateral network of inclined caves forms in this area. In sandwich flow, thin beds of soluble rock are located between impervious beds. A horizontal and lateral network of caves is characteristic.

2.2.2 Karst Aquifers

There are three major zones of flow in a karst groundwater system: the vadose zone (vertical circulation), the high water table zone (horizontal flow), and the phreatic (fully saturated) zone. The water level within the vadose zone tends to oscillate temporally.

At most times, there is both a lateral and vertical exchange between the conduit/cave zone and the phreatic storage/diffuse flow system. Upstream, in the headwater system, the flow tends to become diffuse. As the downstream and spring area approaches, the flow tends to switch into the conduit regime.

Aquifers in karst terrain tend to be unconfined, with free communication between the vadose zone and the surface. Aquifers whose water-bearing rocks are primarily carbonate are classified as carbonate aquifers. The may behave in one of two modes. Flow may be similar to that through sandstones, fractured granites and basalts, or may be uniquely karstic. This flow regime is characterized by integrated systems of conduits, leading to highly localized transport. There is a network of large solution cavities and integrated conduits, or high conduit porosity. The system of karst hydrology has three components: the aquifer itself, a system of surface basins, and a system of groundwater basins. The surface and groundwater basins tend to be closely related. Often, the surface and groundwater basins are alternate routes for the same precipitation. In these cases, the conduits usually provide a bypass for surface flow, and tend to be preferred. Conduit systems may split and branch many times underground. Thus, one basin may discharge in many, widely spaced areas. The number of fully saturated conduits, as well as the chosen flowpath, usually varies with groundwater levels.

Surface water and channel flow tend to share many features. These include channel width-depth geometry, sinuosity, channel braiding, ordered braiding and stream length ratios, and distinct catchment area-discharge relationships. Surface channels tend to adjust widths, rather than heights, to accommodate additional recharge. This seems to occur in conduits as well. Fairly equidimensional channels tend to carry small amounts of flow. Rectangular channels either currently contain large flow, or have a history of high flow rates.

The base flow of groundwater occurs in the dry seasons. Base spring flow is similar; it is fed by the discharge of the diffuse system into the conduits. In karst aquifers where the conduits dominate, the base flow tends to be very low. Where flow is mainly diffuse, the base flow is usually close to the mean flow.

2.2.3 Paleokarst

Paleokarst is detached from the contemporary system of flow. It is covered and often confined by clastic rocks. However, erosion and other processes may break though the caprock and uncover the karst region. In these cases, two periods of karst evolution may occur, separated by millions of years. Similar are relic karsts, which are still attached to the surface but are not evolving further. Often these occur when the surface flow moves, removing the mechanisms of formation. Paleokarst and relic karst may be reactivated when significant changes in groundwater flow occur.

2.2.4 Sediment Transport

Non-karstic aquifers usually do not carry high sediment loads. Since their flow is largely diffuse, the pore diameter and fluid velocity are too low to facilitate transport. Essentially, the interface of these aquifers and the surface acts as a filter. Sediments are left on the top as surface residuum, often taking the form of soil. Conduits in karst aquifers, however, tend to have a high sediment load. The channels and sinks that carry the majority of the surface flow through the vadose zone do not filter sediments, and the conduits are very conducive to sediment transport. The sediment load in karst areas tends to be very high, and is sourced in three ways. Erosion from surrounding terrain tends to be high. In addition, carbonate rocks contain a small amount of non-soluble mineral particles. These are left behind after solution processes. Similar residue is created in the conduits themselves, as a byproduct of solution. In times of low flow, these sediments can be deposited in the conduits, blocking them.

2.3 Surface/Groundwater Interaction

2.3.1 Surface Water Infiltration

The flow regime of bare karst is characterized by very rapid sinking of surface water. As a result, there is very little surface flow. In covered karst, sinking is still present, but to a lesser degree. As a result, there is often surface flow present. Areas of high recent tectonic activity tend to have more developed karst, and thus a greater water circulation. Karst terrain is generally dry on the surface, and is often unsuitable for human settlement.

2.3.2 Interaction Between Groundwater and Overland Flow

Lateral circulation in karst terrain is present in three different areas: overland flow, through flow (in the soil), and subcutaneous flow. The subcutaneous zone is aerated and unsaturated. Flow in this area is normally lateral. Vertical flow may occur after heavy precipitation. The flow distribution in this zone is not uniform. This zone is narrow, typically ranging from one-half to two meters thick. It is located under the normally consolidated soil zone, if one is present. Whether soil is present or not, the subcutaneous zone is at the top of the vadose zone and composed of carbonate rock.

Transmission through the vadose zone occurs via three methods: shaft flow, vadose flow through enlarged joints and fractures, and vadose seepage through small fractures and other features. The seasonal drying of open streamflows often occurs with the lowering of the groundwater level. Oscillations of up to one hundred meters in the groundwater level may occur due to seasonal precipitation, and the storativity of karst aquifers tends to be fairly low.

Karst terrain often acts as a natural flood control. Bare karst areas, especially when dominated by conduits, usually have small and largely spread flood peaks. The presence of soil cover and intact bedrock sharpens these peaks. While the response time of the aquifer is very rapid, the time for infiltrated water to travel to the springs is on the order of days. Overland flow response time is in the order of hours or even minutes. Thus, flash floods are a rare phenomenon in karst terrain, regardless of the precipitation rate.

2.3.3 Karst Springs

Karst springs are common, and usually occur from contact between the carbonate and impermeable layers. Springs are uncommon in areas of heavy water sinking. Early in karst evolution, there are many small springs. As the process proceeds, there tend to be fewer springs but a larger overall flow. The number and volume of springs varies according to the water quantity in the aquifer. Groundwater often appears as springs many kilometers from where it first went underground. This usually occurs when low permeability layers guide that flow to the surface through porous or fractured layers. Karst springs can be classified by the frequency of flow and the source of flow. The outflow may be perennial (permanent), periodic, intermittent, or episodic. Permanent springs are the most common ones and tend to have a large capacity. They never dry, even during drought season. Periodic springs are similar, but are dry during drought periods. Intermittent springs have seasonal flow; they may appear during several months of the year, in the normal period of high precipitation. Episodic springs only appear during flood events or other significant changes in the groundwater level. The spring outflow volume is often dependent on groundwater level, and can account for a large percentage of the discharge. Submarine caves tend to originate from joints, and are usually attached to caves. They are commonly associated with dolines, and are seasonal. Cave springs are similar but are directly and visibly connected to caverns.

Karst springs can also be characterized by the mechanism and nature of their outflow. In free draining springs, the karst rock region is above a valley. The water exits the ground and flows freely, under the force of gravity. This usually occurs in shallow karst. Dammed springs are the most common. The water is forced to the surface when a barrier to underground drainage is present. This barrier may be present in the lithology, as a faulted or conformable contact. Also, fluvial deposits may form a barrier after valley aggradation. Seawater infiltration may force the water upward. Many dammed springs are temporary, appearing when the water table is high. Typically, one permanent dammed spring has several associated high water table springs that appear intermittently. The third type of springs is the artesian springs. These occur when the aquifer is confined by an aquitard or aquiclude. An opening in the layer occurs, usually along fault planes, and the water rises under pressure to the surface. A boil, turbulent upward flow in a spring, is usually associated with artesian springs. Like dammed springs, a single permanent artesian spring may have companion intermittent springs. These rise to the surface when increased pressure makes their flow artesian.

III. ENGINEERING AND ENVIRONMENTAL COMPLICATIONS

3.1 Contaminant Transport

3.1.1 Mechanisms of transport

Karst aquifers have a tendency to transmit rather than naturally treat pollution. This is true for several reasons. Due to the dominance of conduit flow, the surface area available for particle adsorption, ion exchange, and the development of beneficial microorganisms is very low in comparison with diffuse regimes. This problem tends to be greatest in dense, fractured karst. Ideal conditions for contaminant filtration are in porous and clastic rock. In addition, infiltration into the karst system tends to be rapid, through a system of large fractures and sinkholes. This speed leaves little time for the evaporation process. Normally, evaporation in the vadose zone reduces the quantity of volatile chemicals, such as solvents and pesticides. The thin soils and large voids of the infiltration layer also do not efficiently filter particles physically. As a result, sediment and harmful microorganisms often slip through this layer. Once the contaminants are in the ground, the turbulent flow regime in the conduits acts as a rapid transport mechanism. Also, due to this rapid transport, time dependent reactions that decay bacteria and viruses seldom have time to function before the water is discharged on the surface. In laboratory experiments, many bacteria survived for over one hundred days in conduit conditions.[1] This exceeds the residency time for most karst systems.

3.1.2 Contaminant Concentration Equations

The concentration of a contaminant in groundwater is modeled using the following equation:

$$c(x,t) = \frac{c_o}{2} erfc\left[\frac{R_d x - ut}{2\left[R_d D_h t\right]^{1/2}}\right]$$

$c(x,t) =$ the concentration of the solute at a given distance and time

$c_o =$ the source concentration of the solute

$R_d =$ the retardation factor

$R_d = K_d + 1$

$K_d =$ the linear equilibrium sorption coefficient

$K_d = 0.6 f_{oc} K_{ow}$

$foc =$ the fraction of organic carbon in the matrix

$K_{ow} =$ the octanol-water coefficient

$x =$ the distance from the solute source

$u =$ the fluid velocity

$t =$ time elapsed since source release

$D_h =$ the hydrodynamic dispersion coefficient

The concentration at a point along the stream at a given time is affected by two factors that are greatly affected by the presence of fractures, conduits, and caves. The retardation is dependent on the fraction of organic carbon in the soil and the available area for sorption reactions. Porous rock, such as sandstone, has many particles with a high specific surface area, as well as pore space available for the settling of organic carbons. Karst terrain, however, tends to quickly transport sediments, leading to a low organic carbon fraction. And fractures and conduits have far less available surface area, in proportion to volume, than pore flow regimes. Also, contaminant plumes spread faster when the transport velocity is rapid. The velocity in conduits usually ranges from 0.01 to 1.21 meters per second. In the pore flow region of limestone, velocities seldom exceed 1.97×10^{-3} meters per second.[1] Thus, in karst areas with a high density of conduits or caves, contaminants can be transported very rapidly through the conduits and fractures, and far more slowly through the porous aquifer. Not only does this lead to rapid contaminant transport, it often leads to the formation of two distinct plumes, making modeling more complicated and hindering remediation efforts.

3.2 Construction

3.2.1 Foundations

Construction problems associated with karst complications cost over a billion dollars per year worldwide.[6] These problems may have a small to large impact in the construction of foundations for bridges, buildings, roads, and railways. When construction involves a change in the water table, the effects can be large and even catastrophic. Rock slides and avalanches are especially common in carbonate rocks and gypsum. Failure usually occurs along the bedding planes, and is often the result of creep due to fluid infiltration.

Standard practice is to improve the rock mass under the foundation, until it is essentially solid. The depth of treatment should be between sixty and seventy percent of the planned column spacing.[2] The improvement zone should be deeper if the lithology includes folded or sharply sloping strata. Doline development is the problem of most concern, because it can occur suddenly and catastrophically. Dolines can appear in a matter of seconds, causing severe structural damage and loss of life. Sinkholes develop when tension domes collapse. Tension domes are arch and pillar systems that develop from more intact rock, due to the induced suffusion of near-surface sediments into deep cavities. When these arches form and become thin, the structure applies point loads that eventually cause the collapse. The dolines formed may be from one to two hundred meters in diameter and from one-half to fifty meters deep. The sediment erosion is caused by the lowering of the water table across the site, or the focusing of runoff. Focused runoff may be caused by concentrated drainage from structures, as well as leakage from pipes, canals, and sewers. The raising of the water table, though less common, may have the same effect. The saturation of consolidated clay deposits often destroys their cohesion, allowing sediment removal. Also, concentrated loads delivered by equipment, such as trucks and cranes, can cause local collapse. To avoid construction problems, surface geophysical techniques and careful boreholes are recommended.

Structural foundations, especially those for smaller structures such as houses, tend to be built on a uniform raft foundation. These foundations are often placed on top of a layer of soil or another unconsolidated sediment. In karst areas, the load-bearing capacity of the underlying layer is often uneven, due to pillars, fractures, and cavities. Non-uniform compaction of the sediment occurs, resulting in differential settlement beneath the structure. If this differential is high, cracking or other failure of the foundation often occurs. This problem is most common in smaller structures, where geotechnical analysis is likely to be spare or nonexistent. For larger structures, test holes are often drilled in area known to be karst. However, due to the high heterogeneity and variability of karst terrain, these holes are often misleading. A hole drilled may indicated fairly intact rock, despite a cavern located only millimeters away. In order to be effective, test holes must be drilled at the exact location where support points will be located. Even a small, standard practice deviation could lead to useless data.

3.2.2 Tunnels and Mines

Tunnel and mine projects located in karst terrain often face a catch-22: the excavations must be dewatered, but excessive changes in the water table may lead to failure. Tunnels and mines may be located in the vadose zone, shallow phreatic zone, or permanently saturated phreatic zone. In the vadose and shallow phreatic zones, the excavations are usually made on a gentle incline, allowing the water to drain naturally under the force of gravity. The water table is normally not deleteriously affected. Deep excavations require a more aggressive approach. There are three accepted practices. The most common is pumping in the tunnel itself. This pumping usually continues after construction. Unfortunately, failure of the pumps can lead to catastrophic failure, flooding, and loss of life. More accepted is a system of grouting to cut off flow, and pumping of the remaining seepage. This is slightly more expensive in construction, but maintenance costs are lower and the potential for failure is reduced. Both of these methods may have local effects on the water table, leading to the drying of nearby wells and springs. However, the change in the water table is usually too small to cause structural failure. A third method, common in larger structures, is a pumping system that creates a cone of depression encompassing the entire zone, dewatering the zone during and sometimes after construction. This often alters the groundwater table enough to cause collapse dolines. The rock blasting used in foundation and mine development can cause small to medium sinkholes. The solution mining of salt and the water flooding of petrochemical reservoirs is not recommended, as subsidence and even collapse often result from the material removal. The common practice of pressure injection high in salt diapirs is especially risky.

3.2.3 Hydrogeological Response to Regional Flow Changes

After the structure is completed, regional inflow changes may lead to structural problems. Features such as roofs, walls, and driveways tend to form areas of concentrated runoff around the edges. These regions of concentrated flow often form channelized paths through the soil. Soil removal is thus speeded highly and unnaturally. A cavity then forms, often under the structure. This may occur suddenly or gradually. In any case, the cavity often collapses at a certain size, failing the structure. Cavities of up to ten meters in height have been known to form with little warning. Collapse dolines also often occur during or after construction. Cavities, especially those that are not filled with water or sediment, have a zone, often known as a dome, of tension above them. Even deep caves may have tension domes that extend to near the surface. If construction either breaches or overloads this area, the cave will collapse. Subsidence results, often causing building failure.

Sinkhole collapse can also result independently of loading. Any disturbance in the gradient or flux of the groundwater may lead to this failure. Unfortunately, both increasing the recharge of the flow system and dewatering it are potentially harmful. Either practice can lead to more rapid sediment transport, clearing support systems and causing collapse. Increased flow carries more sediment, logically. Lowered flow can also cause this phenomenon. Saturated sediments tend to be more cohesive and harder to disturb. The lowering of the water table dries sediments, destroying consolidation and hastening transport. In addition, saturated flow in caves is changed to open stream flow when the water table is lowered. This flow regime is often more conducive to sediment transport.

The volume of groundwater flow is estimated using the following equations. The only quantity that is not a material property is the hydraulic gradient. The volumetric flow is directly proportional to this factor, if all material properties remain the same. Thus, any change in the regional hydraulic gradient caused by construction activities will affect the groundwater flow rate.

Porous rock: Volumetric Flow $Q = kiA$

$k =$ the hydraulic conductivity

$i =$ the hydraulic gradient

Hydraulic Gradient $= \frac{\partial h}{\partial l}$ (change in head over change in length)

$A =$ the cross-sectional area of study

Hydraulic Conductivity $= \frac{kp_w g}{\mu}$

$k =$ the permeability

$p_w =$ the density of water

$g =$ gravitational acceleration

$\mu =$ dynamic viscosity

Permeability Nd^2

$N =$ dimensionless shape factor

$d =$ mean grain diameter

Fractured rock: Volumetric Flow $Q = \frac{p_w g b^2}{12\mu}(bw)\frac{\partial h}{\partial l}$

Hydraulic Conductivity $K = \frac{p_w g N b^3}{12\mu}$

Permeability $k = \frac{Nb^3}{12}$

$N =$ number of joints per unit distance across the rock

$b =$ the aperture width

3.3 Dams and Reservoirs

3.3.1 Reasons Reservoirs Built in Karst Terrain

Terrain dominated by limestone and dolomite is often selected for dam sites, as it tends to meet two of the main conditions for reservoir construction. This mineralogy lends itself to the development of narrow and steep valleys, reducing dam length and material cost. In addition, when relatively intact, these rocks usually provide sufficient support to tie back the dam during construction and after filling.

3.3.2 Problems Associated with Karst Terrain

However, the jointing prevalent in these rocks usually violates the third condition: the foundation, and abutment rock must be nearly impermeable. In karst terrain, caves in the valley walls and conduits in the floor often increase the permeability to unacceptable levels. When the rock is sufficiently permeable, the filling of the reservoir raises the water table, creating an unnaturally steep gradient across the foundation and abutment areas, threatening structural stability. Also, an excessive rate of flow is released into the surrounding karst terrain, often significantly altering the flow regime. If the force exerted by the new flow is sufficient, it can flush the sediments from long-filled conduits, often reactivating relic karst and paleokarst.

There are special problems associated with reservoirs used for hydropower or flood control. These reservoirs typically have fluctuations of ten to fifty meters. The water table will fluctuate correspondingly. This often leads to the piping of sediments from caverns and fractures, by the processes described above. Often, sinkhole collapse occurs. This phenomenon has been documented up to ten kilometers from the damaging reservoir.

3.3.3 Solutions and Standard Practice

When evaluating the construction of a dam in karst terrain, seven factors must be considered: the lithology; geologic structure; density, size, and connectivity of fractures; the nature and extent of karstification, the physiography of the area, the hydrogeologic situation, and the type and size of the dam.[6] Based on these factors, 7680 scenarios leading to possible failure or significant operating problems have been identified. Suitable for dam construction in limestone and dolomite dominated areas are sites with a relatively simple geologic structure and poor karst development. Due to the high permeability of carbonate rocks, aquicludes at a shallow depth should be present. If a grout curtain, functioning as a vertical cut-off wall, can be extended to the aquiclude cost-effectively, the site is suitable. Many accurate boreholes should be taken prior to planning and construction. Caves in the valleys walls should be filled in before the dam is activated. Usually, the hillsides are mined, and caves found are grouted. These measures will add greatly to the cost of the project, and often outweigh the material savings gained by a relatively narrow dam. In addition, piezometers should be placed downstream. A monitoring program of these and the outflow springs should be implemented during and after the filling of the reservoir.

When the reservoir is filled, the hydrostatic head on the reservoir is increased. A new water table is also established in the valley walls. In karst terrain, solution cavities are usually located below riverbeds. These may be filled with clay or other sediments, but are often open. Also characteristic of karst terrain are dry caves located at various heights in the valley walls. Both of these features provide an easy bypass for flow. Geological features may threaten the integrity of the actual dam structure, causing a possible breach due to instability. However, they usually just act as a drain on the reservoir itself. The increased head, which can be in the order of tens to hundreds of meters, can flush the sediments from the cavities. If the passages are not already open, they will rapidly become so. The grouting of these cracks, or the construction of a grout curtain, is often successful. However, the cost is prohibitive for larger pools. When the water level is raised, the dry caves in the valley wall can become saturated, acting as rapid conduits for flow. No practical or cost-effective solutions for dealing with caves are in standard practice. Lateral tunnels can be constructed and used as the entry point for cave grouting, but the cost is usually prohibitive. This method is only practical if the cavernous area on either side of the reservoir is very shallow (a few meters). However, it is not unusual for karst regions to have lateral cave systems as wide as ten kilometers. In general, any area with long lateral cavernous zones is not suitable for reservoir construction.

Karst terrain with dominant gypsum and anhydrite is usually highly unsuitable for dam construction. Dam construction can lead to the enlargement and extension of the conduit network, the collapse of solution-weakened gypsum and hydrated anhydrite, and the erosion of the dam itself by sulphated water. Extensive grouting of the fracture networks and bedding planes can solve these problems, but the work is expensive and requires frequent maintenance.

3.3.4 Case Study: The Hales-Bar Dam

One example of a reservoir unwisely constructed in karst terrain is the Hales-Bar dam. The dam is located in Chattanooga, Tennessee, and was constructed between 1905 and 1913. Insufficient exploration, even by the standards of the early twentieth century, was made. The foundation was not adequately excavated, and no treatment of regional karst features was made. During dam construction, leakage occurred through the flawed rock of the foundation. This complication quadrupled the original time and construction budget. The budget inflated from three million to nearly twelve million dollars. Originally projected to take two years, the dam was eventually completed in 1913 after eight. However, before the reservoir was even completely filled, leaks were discovered. In 1913, 1914, and 1915, unsuccessful attempts were made to plug the inlets. A survey in 1919 discovered seventeen new karst springs resulting from the reservoir. Nine of the springs seemed to originate from cavern systems to the east of the dam, eight from the west. Between 1919 and 1921, molten asphalt was pumped into the conduits. Holes were drilled as the delivery system, and 78,324 cubic feet of asphalt was used in the project. This action stopped half of the springs, and flow in the remaining ones was reduced. However, by 1930, leakage had returned to 1919 levels, estimated at 1200 cubic feet per second. The state government acquired the property in 1939. At that time, the flow had increased to 1700 cubic feet per second. Thirteen separate streams were found. In 1940, successful action was finally taken, using a combination of fracture grouting and a cut-off wall. The wall, a grout curtain, was constructed of two rows of drilled piles. Each row consisted of eighteen-inch diameter piles at a two-foot center spacing. No surface flow has been traced back to the dam since.[1]

Figure 3.1 Plan View of Reservoir Cutoff Wall

IV. CASE STUDY: THE THREE GORGES RESERVOIR

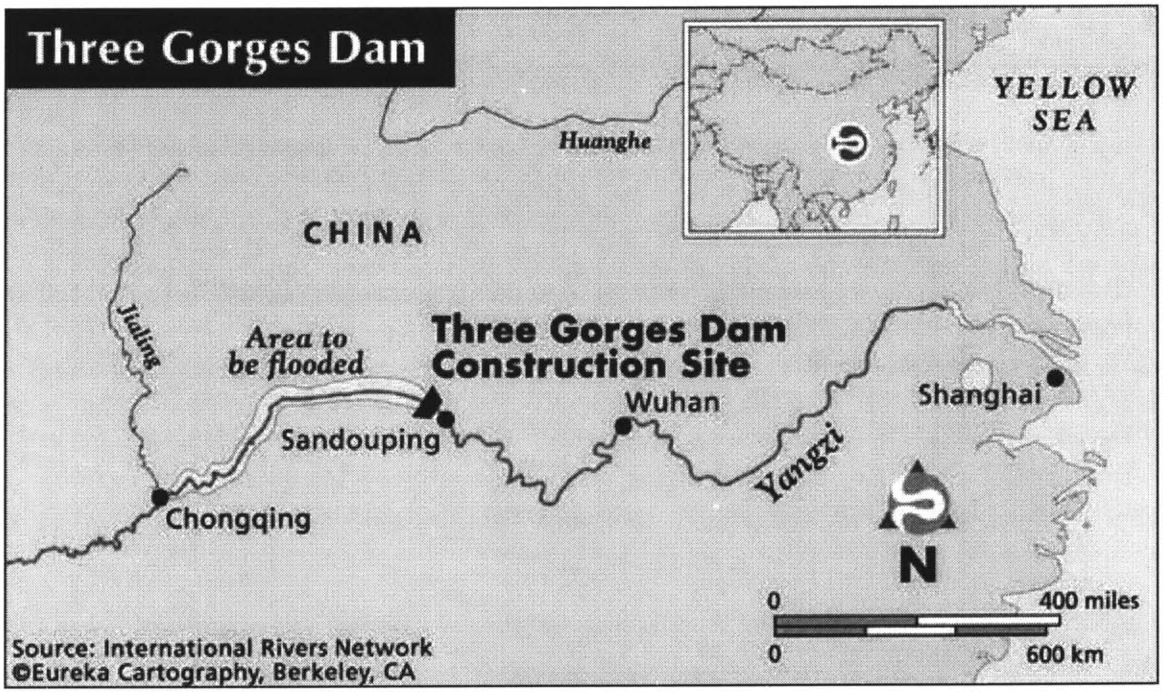
4.1 Project Overview

4.1.1 General Information

A large hydropower project is currently in the construction and operations planning stage in China. When completed, it will be the largest dam and reservoir of its kind in the world. Cutting-edge technology is being used in many areas of the project, but questions have been raised about many aspects of the project, leading to an international protest campaign and the denial of funding from many sources, including the World Bank.

4.1.2 Construction Specifications

The dam is being constructed near the town of Sandouping, in the Hubei province of China. The building site is elevated at one hundred thirty-three meters above mean sea level. At its center point, the dam will have a height of 185 meters. It will bridge a gap of nearly two kilometers. When the dam is activated, approximately 632 linear kilometers back-stream will be flooded. Approximately 30,000 hectares will be inundated, displacing nearly two million citizens. Although the area is mostly rural, nineteen cities and 326 towns and villages will be destroyed. The reservoir formed is projected to have a normal pool level of 175 meters, and a seasonal flood control level of 145 meters. The total storage capacity will be 39.3 billion cubic meters, with a flood storage capacity of 22.1 billion cubic meters. The reservoir should be navigable by ships of up to 10,000 tons, allowing a passage to Chongqing, a growing city currently inaccessible by large watercraft. Projected hydropower generated is 17,680 megawatts. This will be spread equally over 26 discharge and power generating units. Each unit will be capable of generating energy and sluicing sediment-laden and excess water.[11]



Source: International Rivers Network
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Figure 4.1 Reservoir Site[11]

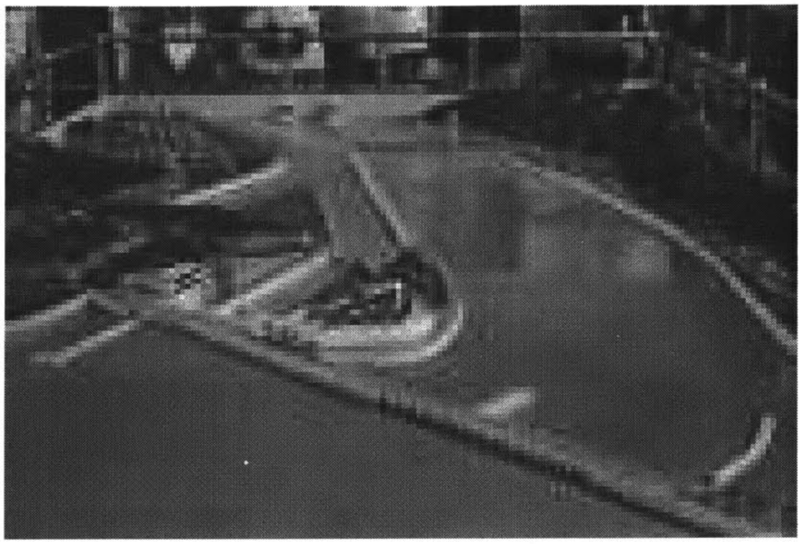


Figure 4.2 Dam Builder's Model[11]

The infrastructure is currently under construction, and the filling of the reservoir will begin in September 2003. The target date for filling to hydropower generation depth, 175 meters, is September 2009.[11]

4.1.3 Project Challenges

The project has proved controversial both at home and abroad. The World Bank has refused funding; the project has not yet passed its human impact, environmental, and engineering surveys. However, they do consider the project financially feasible and have allowed it to reapply for funding. A number of citizens scheduled to be moved to make way for the reservoir have protested. An international information campaign from such organizations as the Sierra Club and the International Rivers network has aired several concerns about the project. These concerns fall into four general categories:

- Archaeological/Historical—Many artifacts are located in the inundation area. Some, such as statues, can be moved. Others, like cliff carvings, will be lost.
- Human Impact—Two million citizens, mostly peasants, will be removed from the area, mostly to areas with less fertile soil. Citizens who depend on the river for their livelihood may find it difficult to adjust, causing great unrest.
- Environmental—Sensitive and often poorly mapped cave environments will be destroyed. Species, such as the freshwater dolphin, may become extinct.
- Engineering Practice—Many aspects of the project rely on unproven technology or make questionable assumptions.

4.1.4 Site Selection

However, despite the complications, there are some excellent reasons for locating the dam at this site. The Yangtse River has an extremely high flow rate, over twenty cubic meters per second at the dam site. This ensures that the reservoir, even if large amounts of water must be discharged or leakage occurs, will remain filled. In addition, the potential energy at the site is very large. The only alternative is a series of dams; no other single site has been found suitable. Several cities upstream of the dam are thriving and their population is growing; it is primarily these nearby communities that are in need of power. In the past few years, floods in the area have been devastating, causing great loss of life. The steep cliffs and narrow gorges provide ideal reservoir geometry, minimizing inundated acreage. The relatively small dam width (for the reservoir size) will minimize material costs. Also, karst terrain tends to absorb a large amount of sediment, reducing the rate at which the reservoir will be blocked. If the project succeeds, it will both provide prestige and possible new operating methods for similar projects.

4.2 Engineering Complications

4.2.1 Dam Breach and Landslide Failure

Highly fractured limestone, valley-side caves, and heavily deformed and layered rock dominate the area where the dam is constructed. Thus, it is difficult to determine the strength properties of the rock. The dam is being "over designed", with a very high factor of safety being used for the foundation and supports. However, the presence of caverns and joints could lead to landslide failure and dam breach. In addition, the very large hydraulic gradient that will be applied across the dam while it is being filled will increase the stress on the system, possibly leading to landslide failure. To prevent this, extensive surface and borehole geophysical studies were undertaken before the dam was designed.

4.2.2 Excessive Sedimentation

There is concern that the inflow of sedimentation could cause sediment build-up, eventually rendering the hydropower plant unusable and causing the reservoir to flood.

China currently operates 330 major reservoirs. Of these, 230 have had substantial problems with excessive sediment deposition. Many of these have lost more than half of their storage capacity. On average, a loss of fourteen percent has been reported.[13]

The average sediment inflow into the source area of the reservoir is 510 million tons per year. Over the last fifty years, this has varied from 210 to 754 tons. The average sediment concentration in the source water is 1.19 kilograms per cubic liter.[13] This value is fairly low, as sediment tends to be carried easily into the groundwater system in karst terrain. The sediment flow is roughly proportional to yearly precipitation. Erosion control measures that have recently been put into place are expected to reduce this value slightly. After the reservoir is filled, a rise in the water level and a slowing of the river velocity is expected to result in sediment deposition in the reservoir. Excessive sediment build-up in the reservoir often leads to a breakdown in the hydroelectric system.

Currently, the dam operators plan to solve this problem by using the "retain and discharge" method. The reservoir level will be lowered, speeding flow, when the water is highly contaminated. When the water is fairly clear, the level will be raised, retaining the clean water. The period of high sediment contamination is expected to coincide with the flood season, from May to September. A design pool of 145 meters has been chosen for the "discharge" period. A large amount of water entering the reservoir will be vented through the sluice gates. In September, the pool will be allowed to fill an additional thirty meters with supposedly cleaner water. However, only 30-40% of the sediment, according to current models, will be removed by this method. Current projections by the designers are that the reservoir will be reduced to 86% flood control capacity and 92% power generation capacity after eighty years. However, this figure assumes that the weather will follow a typical pattern and erosion control is highly effective. It also ignores upstream effects of the dam. In addition, this method of sedimentation control is untested, so the conclusions are purely theoretical.[13]

Some sediment will build up, but the designers believe that it will reach an equilibrium value within seventy to one hundred and fifty years. At this point, the sediment bed will have a slope that eases transport, preventing future build-up. This procedure has been used with seventeen other reservoirs. Seven of these are in China; one is in the United States. The largest one has less than a fifth of the capacity of the Three Gorges. None of these dams has reached its equilibrium point, so the method remains unproved and poorly tested. In addition, measurements of sediment production and transport for the next hundred years have been made, using several mathematical and physical methods. However, many assumptions that are not backed up by experience or practice were used. According to current experience, fifty-year sediment forecasts are unreliable, and one hundred-year forecasts nearly useless. The main source of error is the predictions of sediment accumulation. Even when inflow rates are correct, the deposition rates tend to defy prediction. These rates are especially unpredictable in multipurpose reservoirs such as the Three Gorges. Similar reservoirs in India have exceeded their deposition estimates by as much as 775 percent. According to current estimates, the reservoir should be in equilibrium when ninety to ninety-five percent of the sediment entering passes through the reservoir. The discharge of silt-laden water in the summer presents several problems in operation. During the time of highest inflow, the reservoir cannot be filled to provide power in the drier winter. Also, flood storage may be needed at these times, as high precipitation rates and high sediment rates tend to coincide. Thus, when water is stored to prevent flooding, high sediment accumulation may occur. The sediment may settle permanently. This condition is not provided for in any estimates. If very careful monitoring is undertaken, the rates may be adjusted to accommodate this, but in practice these schemes are seldom correctly carried out and require large budgets.[13]

Also, the forecast of the final slope of sediment may well be thrown off by several factors, including large inflow fluctuations caused by flooding. If the slope were too steep, deposition at the head of the reservoir would be excessive, leading to flood events. No case studies were used in this estimate, only models and equations. Similar dams, including the Sanmexia dam in China, have experienced steeper slopes than forecast. Often, remedial action is needed within the first few years of operation. Another problem is the percentage of gravel-sized sediment at the head of the reservoir. In the design calculations, the percentage of gravel was deemed insignificant, and it was not taken into account. However, independent reports indicate that two hundred thousand cubic meters of gravel may accumulate in the reservoir yearly, requiring dredging. While the majority of the sediment will be sand or silt size, the gravel size sediment will tend to accumulate at the head of the reservoir. These may form a slope unfavorable to flood control and navigation, interrupting activities and requiring regular remediation. In addition, the outflow of silty water may damage the outflow streams. Erosion of the banks, even the critical levee system, is possible. Also, the sediment-laden water may damage and wear the discharge system itself, requiring frequent replacement.[13]

The successful and safe operation of the dam depends on the accuracy of these sediment flow models. However, there are many flaws in the assumptions made and parameters used to determine the slope. Excess sedimentation could well lead to a loss of hydropower and, worse, a failure of the flood control system.

4.2.3 Lack of Impermeability

Generally, it is preferred that reservoirs be located in areas with fairly impermeable bedrock or sediments, such as intact granite or clay. This insures that the reservoir will be able to maintain the design pool level, and prevents substantial changes in regional groundwater flow. At the Three Gorges site, leakage will occur both through the conduits in the valley floor and caves in the valley walls.

The Three Gorges project has been following some of the standard practice recommendations for karst reservoirs to limit leakage and regional flow changes. A system of grouting in the reservoir floor conduits is planned; all shafts and fractures greater than two millimeters in aperture will be blocked. An extensive geophysical survey has been done at the dam site and the surrounding area. Careful attention has been paid to borehole exploration; many of them have been drilled in the exact location of anchors and tiebacks, rather than depending on cross-sections for design. A monitoring program for the period of pool rise has been planned. Piezometers will be placed upstream and downstream of the dam. These will be monitored, along with springs activity, while the reservoir is filled.

However, several recommendations are not being followed. No grout curtain is being used, as extending piles to the aquitard would be prohibitively expensive. Grouting of the caves is not being undertaken, for the same reason. And due to the accelerated schedule of the project, the reservoir is being filled very rapidly, at nearly twenty-five meters per year.

Thus, it is reasonable to believe that large changes in groundwater flow may be present. The rate of pool rise is likely to provide inadequate time for equilibrium to occur during the monitoring period, leading to, among other things, drastic changes in spring flow. This study will attempt to show the areas where spring flow may occur just after planned pool levels are obtained in 2009, during both the flood control and hydropower pool stages.

4.3 Karst Hydrogeology of China and the Site

4.3.1 Karst in China

Mainland China contains over 1.3 million square kilometers of carbonate rocks outcropped at the surface or slightly covered. This amounts to about one-seventh of the land surface. When covered and buried rocks are included, almost one-third of China has a stratigraphy with significant carbonate rock content. Most kinds of carbonate rocks are represented in some area. These rocks are primarily limestone with an average porosity of two percent and dolomite with an average porosity of four percent. The karst terrain is not evenly distributed; it is primarily located in Southern and Eastern China. Over twenty-five percent of China's water resources are carried in karst features.[10]

The total volumetric flow of groundwater in China is 203.97 billion cubic meters per year. This accounts for about twenty-five percent of groundwater in the country. However, these resources are unevenly distributed by both area and season. The water is controlled by soluble rock and feature geology in the karst regions. In South China and the dam area, conduit flow dominates.[10]

4.3.2 Regional Geology

The recharge and discharge area of the Three Gorges Dam includes parts of the Hubei and Hunan provinces of South China. Carbonate rocks in this area fall into three general categories. Limestone encompasses about seventy percent, dolomite twenty-five percent, and various insoluble rocks the remaining five percent. Karst terrain is most pronounced in the Western area of the Hunan and Hubei provinces. Carbonate rocks dominate this area of the Hubei. Most are of Triassic and Cambrian origin. A substantial number are of Sinian and Ordovician genesis. The western area of the Hunan province has similar lithology, but Devonian and Carboniferous limestones are also well represented. In both areas, the karst terrain is alternative rather than continuous. The limestone is intercalated with non-carbonate rocks beds. These are primarily sandstones, shales, and basalts. Folding is the primary mechanism of deformation in this area. Due to this, and the sedimentation sequence, these beds tend to occur in alternating longitudinal belts. In the Northern and Southern area near Changjiang, the terrain is very mountainous. Very deep gorges are formed. Elevation may vary within a region from eighteen hundred meters to two hundred meters. The geological features in this area are highly sensitive to changes in water flow and level. They will be affected by the rise in water level due to reservoir construction; opinions vary as to the extent. Western Hubei contains isolated systems of karst, both of syncline and anticline origin. They tend to be extensive, such as the Changyang anticline, which is over 100 kilometers long. The Yuntai Luang syncline, near Qingjiang, has a similar scale. Fluvial erosion is dominant in the formation of geological characteristics in western Hunan and Hubei. Many river caves are formed, especially in the limestone of the Qingjiang valley. The Tenglong cave, near Lichuan in Hubei, has a subterranean river over ten kilometers long. Over thirty-seven kilometers of large subterranean caves have been surveyed in this area. Other fluvial characteristics evident in both regions are dry valleys, vadose caves, and closed karstic depressions. Flow within the Yangtse gorge area is especially significant. This karst system is largely permeable (with a coefficient of 75,000 meters per day). The velocity of groundwater flow varies regionally and seasonally, from 834 to 7488 meters per day. Western Hunan has a system of fairly linear undergrounds rivers, through a system of connected caves. Nearby, South and East Sichuan contain smaller and steeper folds. The synclines and anticlines range from three to thirty kilometers. Triassic limestones, forming narrow karst belts, dominate the anticlines. Hilltop karst valleys are typical of the region; large lakes are formed at elevations of up to five hundred meters. Thick, jointed limestone forming pillars and large collapse pits are common in this area. Central and South Hunan have more moderate folds. Devonian and Triassic limestones dominate. The allogenic rise of water in non-limestone outcrops dominates feature formation. This process forms many small and large-scale caves.[10]

4.3.3 The Yangtze River

At the construction site of the dam, the flood flow of the river has reached 75,000 cubic meters per second. Average flow at the mouth of the river is 32,620 cubic meters per second. Of this, 8790 cubic meters come from tributaries that enter before the dam, 9090 cubic meters comes from tributaries that enter downstream of the dam, and 14,740 cubic meters comes from direct run-off and groundwater recharge. The flow at the dam, currently, is on average 20,899 cubic meters per second.[2]

4.3.4 Regional Hydrogeology

In areas of a low water table, valleys tend to carry the majority of the water. In times of uplift, unified groundwater streams tend to separate into several streams. When subsidence occurs, isolated streams prefer to unify. Near the surface, fracture and diffuse flow are dominant. In an intermediate zone a network of small conduits exists. These are often three-dimensional, facilitating both horizontal and lateral water exchange. In the deep zone, conduits are usually large, and caves are frequently included in the system. These conduits are horizontal or gently sloping, and do not facilitate vertical water exchange. Flow in these conduits may be very rapid, and behave similarly to surface water. Groundwater tends to collect in area of local denudation, as well as areas of favorable geology. Flow in the plain and plateau area is typically unconfined. In the deep basins, a confining area is typically present. Most hydraulic characteristics, including depth of flow, hydraulic conductivity, and volume of flow, tend to fluctuate regionally and seasonally. Thus, this terrain seems to be highly sensitive to changes in the water table, such as those brought on by reservoir formation.[7]

In areas upstream of the dam where fractured limestone is dominant and the gradient is unusually steep, large systems of karst springs are very common. These commonly consist of a permanent spring, with several intermittent springs accompanying it. The exiting water is often sediment-laden and turbulent. It tends to exit as a dammed spring, which means that the springs are associated with the confining layers.[12]

4.3.5 Site Geology

The study area is primarily, about 85 percent, fractured limestone. It is highly folded, dominated by one anticline. A network of small conduits begins near the surface. About a hundred meters down, the conduits become larger and more horizontal in nature, rapidly transporting flow. The confining layers present are mainly slightly weathered shale. This area has been primarily defined by surface geophysics and geological mapping, although some borelogs have been taken at the construction site.[3]

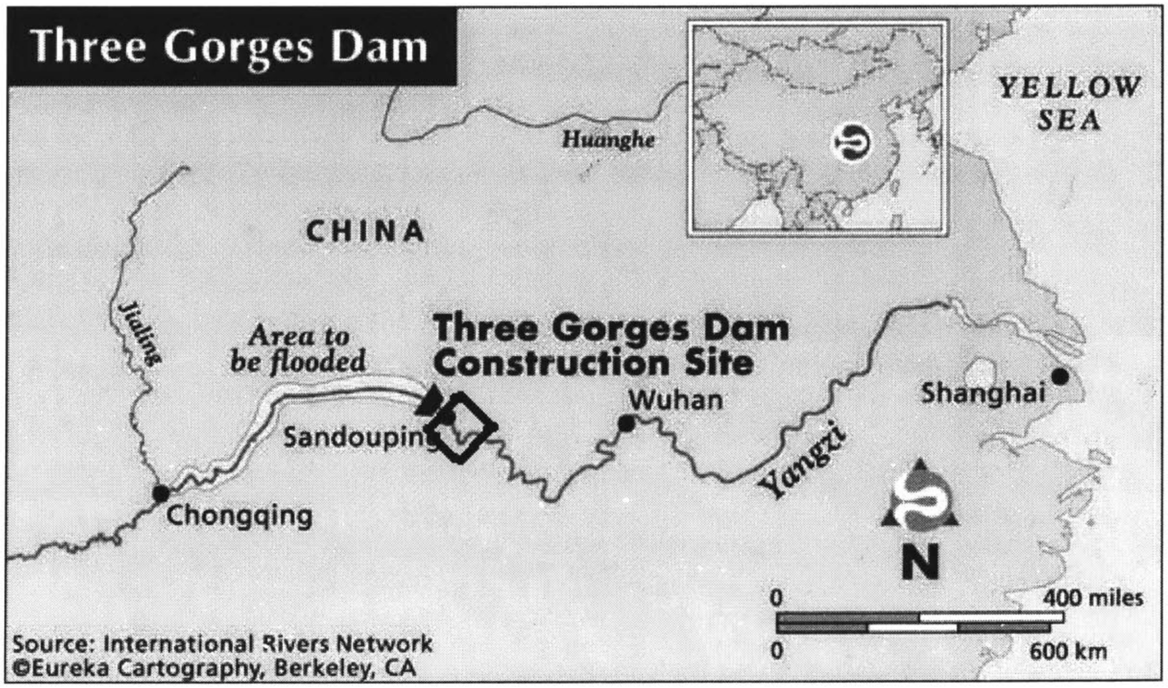
4.4 Method Selection

There are several study methods currently in use to map and characterize karst aquifers. Included are cave maps, dye traces, pumping tests, remote sensing, spring and stream hydrograph analysis, geochemical methods, surface and borehole geophysics, geomorphology, computer modeling, and lab experiments. None is entirely adequate alone. Computer modeling is one tool that has been adapted to karst modeling. Several programs have been designed to specifically model karst aquifers, but they are hard to obtain and the memory requirements are very high. Thus, usually more common models are adapted for karst use. MODFLOW is one such model. It was designed to model pore flow, but has been successfully adapted for fracture and conduit flow by using equivalent hydraulic conductivities. Fractured areas are normally modeled as isotropic blocks, as fracture flow averaged over a large area tends to be nearly isotropic. Conduits are given different conductivities in each dimension, as lateral flow tends to dominate. However, the modeling method does have limits. Regardless of the exploration method used, there is usually insufficient data on fracture conductivity, position, and connectivity. Thus, the hydraulic conductivity for areas containing conduits is averaged over the entire block, based on the predominance of the conduits in the cross-sectional area. Interpore flow is ignored in these blocks, as the conduit flow characteristically dominates.[1]

4.5 Parameter Selection

4.5.1 Study Area

The selected study area extends one hundred kilometers along the river. The centerline of the study area connects the dam at Sandouping and a low-level lake. The lake is approximately 280 kilometers from the dam. The centerline begins 7.2 kilometers upstream of the dam site, and terminates far before the lake. The width of the study area is also one hundred kilometers, at right angles to this line. I chose this area for several reasons. It has a fairly consistent lithology, being primarily fractured limestone, and is dominated by a single syncline. Also, large karst springs have appeared in similar geology upstream, and it is logical to believe that changes in the flow rate will produce similar springs here.



Source: International Rivers Network
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Figure 4.3 Study Area

4.5.2 Model Parameters

The grid measures one hundred by one hundred blocks, each representing one square kilometer. I modeled two layers, each with a thickness of two hundred and fifty meters. The following parameters were modeled:

Year 2003 (before dam is filled)

- Hydraulic conductivities
- Recharge rate
- Elevation blocks
- River head, bed elevation, bed conductivity, and bed thickness

Year 2009 (after filling is completed)

- Same for 2003
- Add constant head polygon (along stream line, 7.2 kilometers long, 2 kilometers wide, two different values for the hydropower and flood control stages)

4.5.3 Hydraulic Conductivity

The hydraulic conductivity values were determined from borings taken at a shiplock site three kilometers west of the site. I entered eleven different zone hydraulic conductivity values for the model. The confining rocks were given one value, while limestone was classified into ten groups. Intact and fractured limestone were defined by textbook values. These were treated as homogeneous quantities. Sections of limestone with significant conduit flow were classified according to two factors: the percentage of fractured limestone with significant conduit flow, and the horizontal or three-dimensional nature of the network. Kx was defined as the gradient flow, Ky as the lateral flow, and Ky as the vertical flow.[3]

Primary Rock Characterization	Kx (m/s)	Ky	Kz	Zone#
intact limestone	1.00E-06	1.00E-06	1.00E-06	1
fractured limestone	1.00E-05	1.00E-05	1.00E-05	2
fractured limestone, conduits less than 2% of area, roughly horizontal	1.00E-04	1.00E-05	1.00E-05	3
fractured limestone, conduits 2-5% of area, roughly horizontal	1.00E-03	1.00E-05	1.00E-05	4
fractured limestone, conduits 5-10% of area, roughly horizontal	5.00E-03	1.00E-05	1.00E-05	5
fractured limestone, conduits greater than 10% of area, roughly horizontal	1.00E-02	1.00E-05	1.00E-05	6
fractured limestone, conduits less than 2% of area, 3-D network	1.00E-04	1.00E-04	5.00E-05	7
fractured limestone, conduits 2-5% of area, 3-D network	1.00E-03	1.00E-03	5.00E-04	8
fractured limestone, conduits 5-10% of area, 3-D network	5.00E-03	5.00E-03	2.50E-03	9
fractured limestone, conduits greater than 10% of area, 3-D network	1.00E-02	1.00E-02	5.00E-03	10
intact confining rocks (shales, etc.)	1.00E-08	1.00E-08	1.00E-08	11

Table 4.1 Model Hydraulic Conductivity Values

Below is the plan view for the top layer. The background value is fractured limestone. The darkest color represents the confining layer of the folded shale. The other values are intact limestone, or conduit-containing terrain. The conduits in this top layer are primarily three-dimensional, and usually do not take up more than five percent of the rock matrix. Note that the zones in the layer do not represent conduits or caves, but merely blocks that contain these features. Remember that the rock matrix is still primarily solid or slightly fractured.[3]

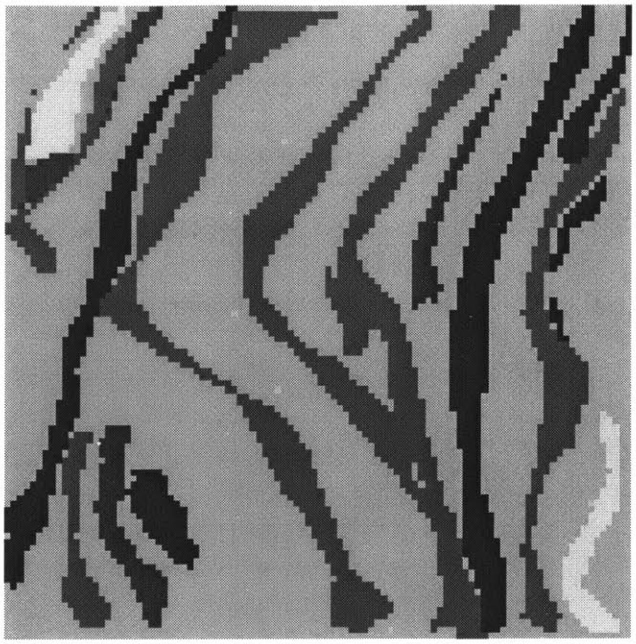

Figure 4.4 Top Layer Plan View

This is the plan view for the lower layer. The left confining layer represents the bottom of an anticline, the right one the beginning of another fold. Again, the background value is fractured limestone. The other blocks, once again, represent areas with conduit flow. The conduits in this area are primarily horizontal; there is very little vertical exchange. These types of conduits often act as a bypass for flow, and thus tend to occur away from the river path.[3]

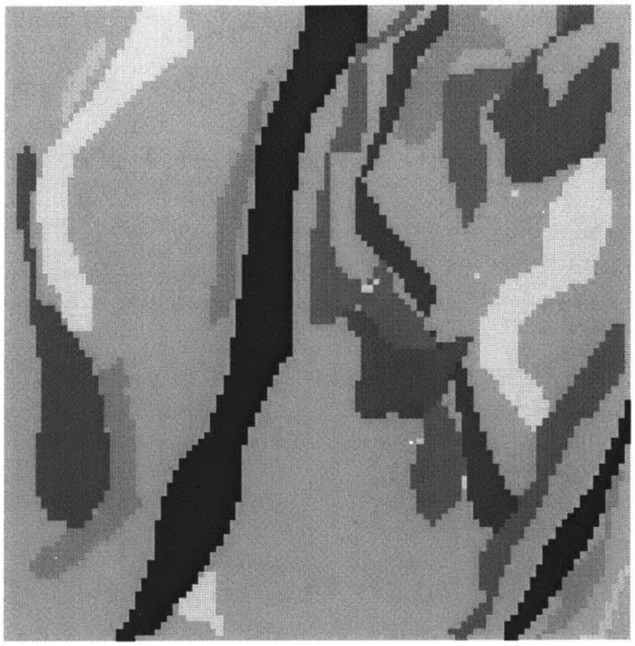

Figure 4.5 Bottom Layer Plan View

4.5.4 Recharge Rate

The recharge rate was obtained by taking the values for precipitation, stream gain, and evapotranspiration over the study area. A forty-year average, from 1951 to 1990, was used for this purpose. Most flow data in this area comes from the same forty-year study. The recharge was held constant over both layers.

- Average annual rainfall = 120 centimeters
- Average annual evapotranspiration = 57 centimeters
- Average stream gain = 9 centimeters (total of 2.33 cubic meters per second)[12]
- Average aquifer recharge = 54 cm/year or .15 cm/day

4.5.5 Top Layer Elevation

The elevation was contoured in five-meter interval blocks. The highest value was 145 meters, the lowest 100. This data was digitized from topographical maps published by the CIA (the most detailed source available). Only top elevation was entered, and only on the uppermost later.

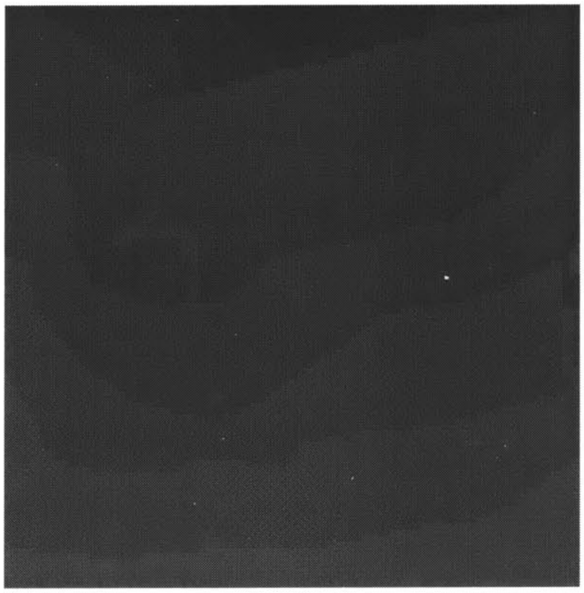

Figure 4.6 The elevation blocks[8]

4.5.6 River Data

The river head and bed elevation were taken from site specification data. At the dam location, the elevation of the riverbed is 133 meters, and the depth of the water is 4.4 meters. The head here is 137.4 meters. At the base, the bed elevation is 97 meters, and the depth of water 4.1 meters, for a head of 101.1 meters. At the head of the river, the bed elevation was taken as the land elevation at the site, 136 meters. The depth was assumed to be 4.4 meters, since the river is largely unchanged along the 7.2 meters between the top of the study area and the dam. Due to a lack of data, the bed thickness was left at the default value, one meter. The hydraulic conductivity of the bed was taken as 10^{-5} meters per second, at the high end of the range for poorly sorted, unconsolidated, largely fine-grained sediment. An average width of two kilometers was used.[11]

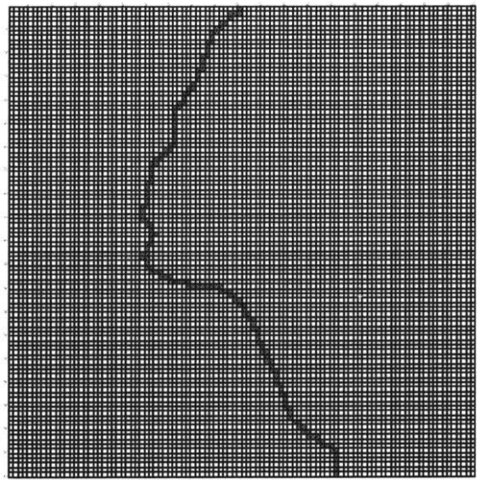

Figure 4.7 The River

4.5.7 Constant Head Conditions

The constant head boundaries were assumed using a worst-case scenario; that the conduits in the floor leak upon filling. Thus, the head added by the dam was added to the current head of 137.4 meters at the dam. For hydropower, it was modeled as 312.4 meters. For floor control, the value was 282.4 meters. The constant head boundary follows the river between the low-permeability formation (top of model) and the dam. It is 7.2 kilometers long and two kilometers wide.[11]

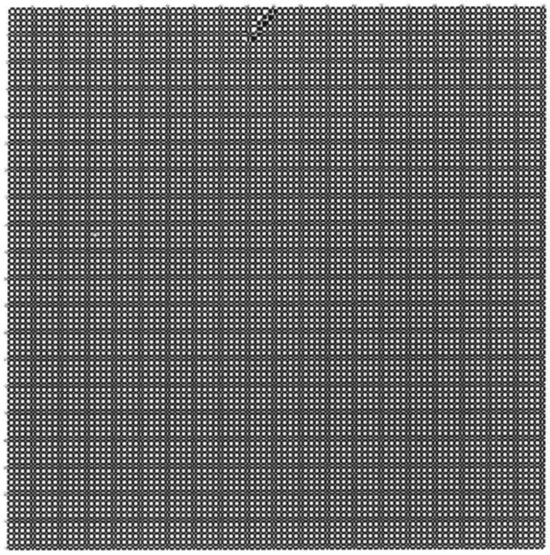

Figure 4.8 Constant Head Boundary

4.6 Analysis

The model was then run through GW Vistas for each of the three scenarios: baseline, hydropower, and flood control. It failed to converge until a condition of 0.5 was applied, likely due to the order of magnitude differences in hydraulic conductivities.

4.7 Predictions

The head will be raised by several meters, even tens of kilometers from the dam. The potential area for spring appearance, where the piezometric surface is above the elevation, will grow. Many new springs will appear, increasing both in flow and number as the dam is filled. These springs will be concentrated close to the dam; those that occur further away will be mainly in low-elevation areas. A large number of these springs will be intermittent, appearing only during the hydropower season and disappearing when the pool is lowered. Existing permanent springs will develop companion springs, either permanent or intermittent. There will be very few episodic springs, as the fluctuations due to flooding should be lowered by the flood control program and episodic springs are normally associated with flood events. Those that currently exist will probably become vehicles for permanent or intermittent flow. Springs that are currently intermittent are likely to become permanent. While some of the springs may be free, the majority will be dammed, brought to the surface when fractured rock and conduits encounter a confining layer. The large shale fold in the area is a likely concentration point. Some of the springs, especially those that are far away from the site in lower elevation areas, will boil, or exit with highly turbulent flow.

4.8 Results

4.8.1 Head Contours

Head Contours, Year 2003

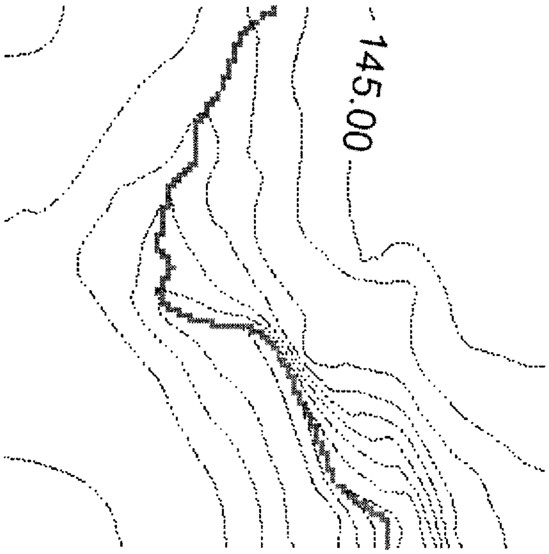

Figure 4.9 Upper Layer Highest = 145 meters Lowest = 105 meters

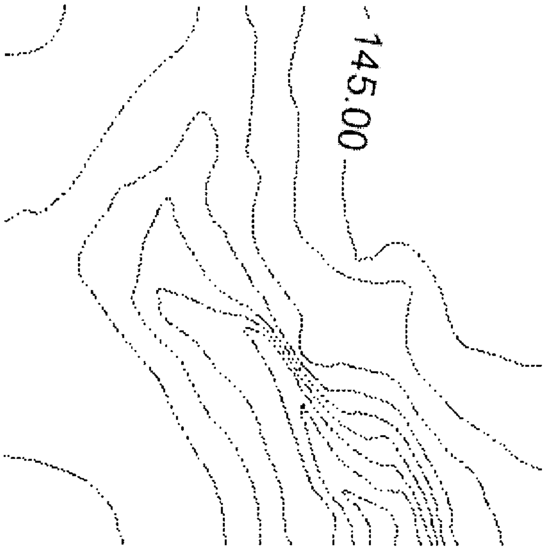

Figure 4.10 Lower Layer Highest = 145 meters Lowest = 105 meters

Head Contours, Year 2009 (Flood Control)

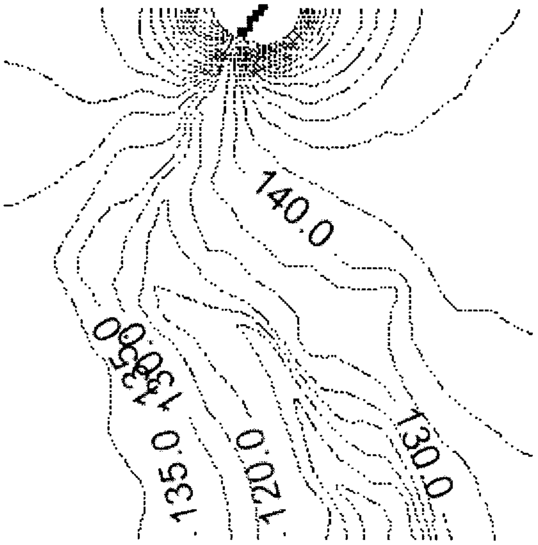

Figure 4.11 Upper Layer Highest = 215 meters Lowest = 105 meters

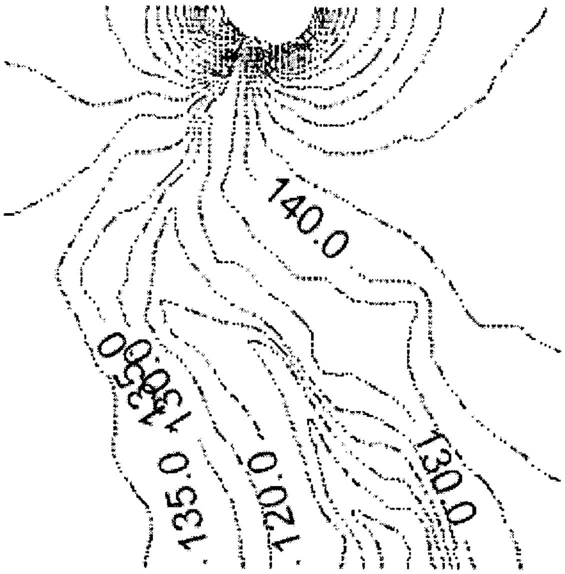

Figure 4.12 Lower Layer Highest = 215 meters Lowest = 105 meters

Head Contours, Year 2009 (Hydropower Generation)

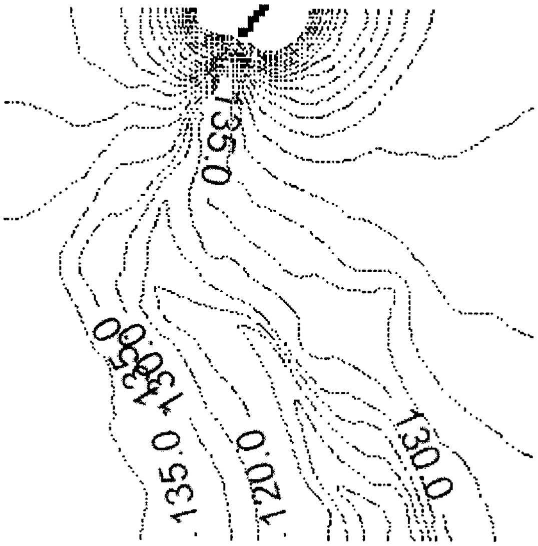

Figure 4.13 Upper Layer Highest = 220 meters Lowest = 105 meters

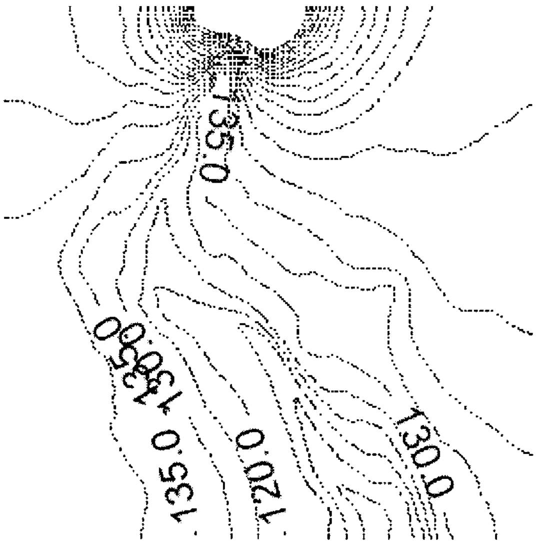

Figure 4.14 Lower Layer Highest = 220 meters Lowest = 105 meters

4.8.2 Hydraulic Gradient

The hydraulic gradient was taken on either side of the stream, two blocks out, following the streampath. These values were then averaged. Groundwater flow is proportional to the hydraulic gradient. A large hydraulic gradient around the dam, which quickly drops off, indicates a large amount of groundwater loss through springs in the area of large gradient. This, fortunately, also indicates that groundwater changes may be locally confined.

2003: 0.00031 (normal)

2009 (flood control): 0.00068 (very high)

2009 (flood control, beginning 5 km downstream from reservoir): 0.00033 (normal)

2009 (hydropower): 0.00071 (very high)

2009 (hydropower, beginning 5 km downstream from reservoir): 0.00033 (normal)

4.8.3 Spring Potential

There is potential for spring appearance in areas where the hydraulic head is greater than the elevation. These areas have been highlighted in white below for each of the scenarios. While the potential for spring flow is present throughout the area, the springs are most likely to appear near confining geological features, such as the folded shale visible in the hydraulic conductivity map.

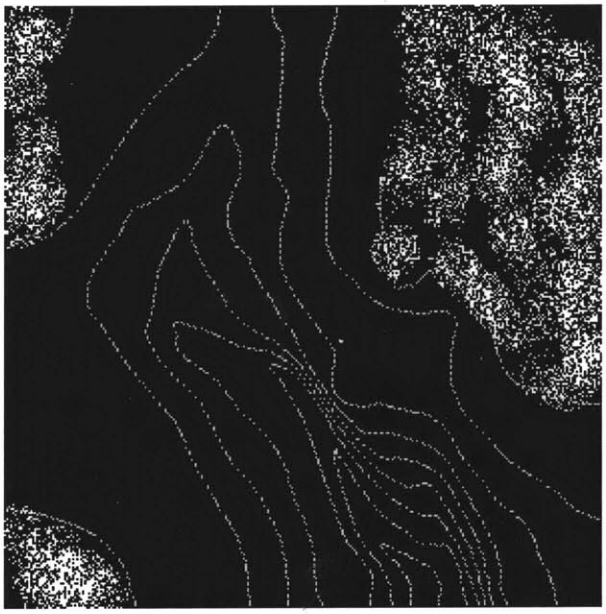

Figure 4.15 Areas with hydraulic head greater than elevation (likely spring activity) – 2003

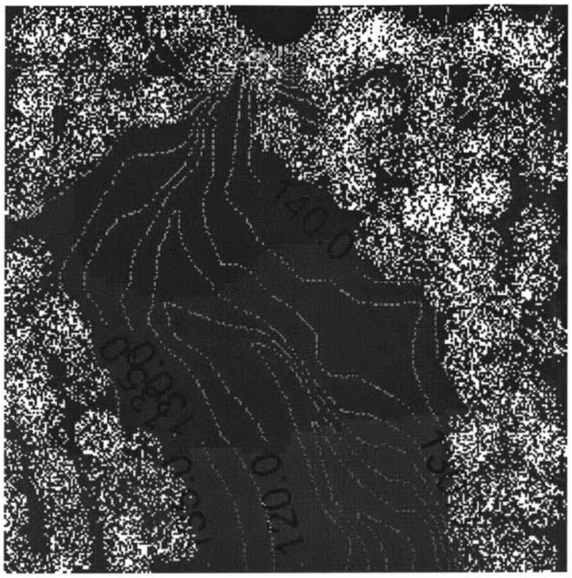

Figure 4.16 Areas with hydraulic head greater than elevation – 2009 flood control

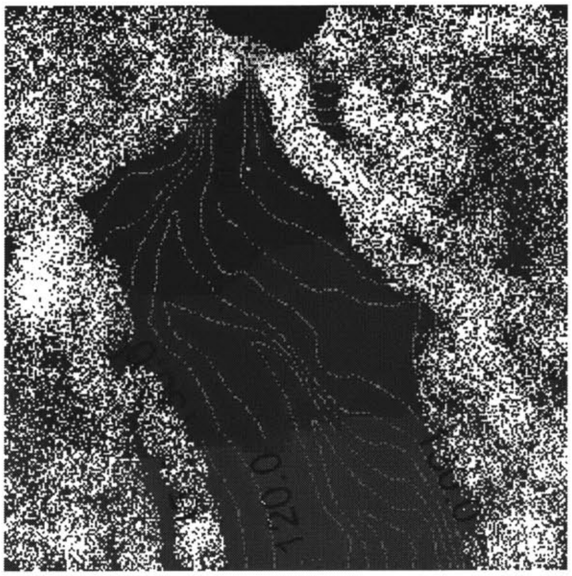

Figure 4.17 Areas with hydraulic head greater than elevation – 2009 hydropower

Average hydraulic head-elevation difference in year 2003 (spring-generating area): 1.9 m

Flood Control

Average in year 2009 (spring-generating area): 18.7 m

Average in year 2009 (spring-generating area outside of 180-meter head line): 4.1 m

Hydropower

Average in year 2009 (spring-generating area): 19.3 m

Average (spring-generating area outside of 180-meter head line): 4.2 m

4.9 Conclusions

In the upper right and left hand corners of the model, as well as the lower right hand sector (where there is probable small spring flow currently), permanent springs will gain flow and possibly companions, while intermittent springs will become permanent. In the areas where the flood control and hydropower spring potential areas overlap, permanent springs will form. In the areas where only the hydropower head leads to spring potential, intermittent springs will form as well, drying up seasonally when flood control is implemented. The springs will be concentrated in the high head and gradient areas around the dam. Since spring flow in karst terrain is generally dammed, the springs will probably be most concentrated around the folds of shale. Stream flow may be sudden and violent at first, but the process of stream formation should serve to help regulate the water table. Equilibrium should be reached within a few years of reservoir filling. Of course, the equilibrium state will change seasonally, as the water level is changed. In addition, flood events may cause up to forty additional meters of head, temporarily interrupting the equilibrium state. Generally, large spring flow changes should be localized, and may even be beneficial downstream, where once intermittent springs will now supply water year-round.

4.10 Recommendations

These regional flow changes are not great enough to jeopardize the practicality of the project. The flow of the river is so great that, even with substantial leakage, the reservoir will be able to sustain the design pool levels. Also, the head gradient is not sufficient to threaten the stability of the structure. However, increased monitoring, especially during periods of fluctuation, is recommended.

It is suggested that the operators increase the time for dam filling to 9 years (interestingly, the original plan). This will reduce the rate of increase to 16.1 meters per year, well within proven practice. Careful monitoring of springs and piezometers should be undertaken. Relocation of citizens to within ten kilometers of the dam should be postponed until the water flow has stabilized.

V. Conclusion

As the difficulties encountered with MODFLOW demonstrate, current methods for mapping karst hydrology are inadequate, as they fail to fully express the intricacies of conduit hydrogeology. As construction projects increasingly incorporate karst terrain, and as pollutant-releasing industies move into karst areas, it is necessary that new methods and technology be developed.

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