Karst Hydrogeology of the Georgia Power Plant Hammond Surface Impoundment AP-3, Floyd County, Georgia, and Impacts on the Fate and Transport of Coal Combustion Residuals

Submitted to

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By

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September 10, 2021

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List of Abbreviations

AP-3: Plant Hammond CCR surface impoundment AP-3
CCR: Coal Combustion Residuals
EPD: Georgia Environmental Protection Division
GPC: Georgia Power Company
USGS: United States Geological Survey
UNESCO: United National Educational, Scientific, and Cultural Organization
WKU: Western Kentucky University

1. Summary

I completed an analysis of hydrogeological conditions at Coal Combustion Residual (CCR) Surface Impoundment AP-3 at Georgia Power's Plant Hammond facility in Rome, Georgia, with a focus on karst geology, which describes areas where dissolution of limestone bedrock results in features such as caves, underground rivers, and sinkholes. The presence of sinkholes and extensive networks of voids in the Conasauga limestone beneath Plant Hammond in the vicinity of AP-3, which have been known at least as far back as the 1970s, indicates extensive karst development. Inconsistencies between the narrative of Georgia Power's *Permit Application (Part B), AP-3 – Inactive Surface Impoundment* (herein referred to as Part B Application) and the actual data in the application indicate that integrity of the relevant hydrogeologic characterization has been compromised through omission, unsupported claims, and incorrect analyses. In one particularly egregious example, while Stantec's *History of Construction* in the application concluded that "No structural instability issues have been observed for AP-3", in fact in July 1977 a sinkhole opened up directly beneath AP-3 and approximately one million gallons a day were lost downward into the karst aquifer below AP-3. Discussion of this collapse and groundwater contamination event was wholly omitted from the narrative of the application. Indeed, although another sinkhole 58 feet in diameter also appears to have opened up beneath AP-3 two years later, the only indication of any sinkhole activity at AP-3 shows up on a diagram (Drawing Number J-51-6), without explanation, over 1,200 pages into the application. While the application also indicated that "Solution features on the order of a few inches up to almost one foot have been documented in some boreholes," data show that in reality numerous, in cases much larger voids have been documented.

Loss of drilling fluids in numerous wells indicates that the karst aquifer beneath the site consists of an extensive network of continuous karst drainage features, or else these fluids would have had no place to go. This squarely contradicts a major, but unsupported, claim made at several points in the application that data do "not indicate laterally continuous karst features within the bedrock."

A broader and perhaps more fundamental error involves flawed analysis of permeability/ hydraulic conductivity data. Georgia Power left out data which has allowed for a mischaracterization of key descriptors of the site hydrogeology.

In my opinion this application has *not* shown that the current conditions with regard to karst environmental risks have been eliminated. There are numerous inconsistencies between the narrative and the actual data in the application indicating that integrity of the relevant hydrogeologic characterization has been compromised. Any evaluation of impact of karst-related risks at the site would begin with an objective, thorough, and transparent investigation of the hydrogeology at AP-3, which is lacking in Georgia Power's application.

2. Introduction

The purpose of my analysis was to review data on hydrogeological conditions at Coal Combustion Residual (CCR) surface impoundment AP-3 at Georgia Power's Plant Hammond facility in Rome, Georgia, with a focus on karst geology. This report provides my comments and analysis on the Draft Closure/Post Closure Care Permit for CCRs (Draft Permit) at the Plant Hammond AP-3 issued by the Georgia Department of Natural Resources, Environmental Protection Division (EPD).

Although closure is already complete, according to the 2015 *Notification of Intent to Initiate Closure* (Part B Application pdf p. 1290), Georgia Power's plan was to leave the CCR in place and close AP-3 "in a manner that will control, minimize or eliminate, to the maximum extent feasible, post-closure infiltration of liquids into the waste and releases of CCR, leachate, or contaminated runoff to the ground or surface waters or to the atmosphere." The specific question addressed by this report is how the presence of karst conditions might influence Georgia Power's decision, and EPD's concurrence, to close AP-3 in place, leaving behind the CCR.

My analysis included consideration of the following materials, with pages numbers referring to .pdf pages in the indicated documents:

1. Permit Application (Part B), AP-3 – Inactive Surface Impoundment, Stantec, November 2018 (Part B Application)
2. Notification of Intent to Initiate Closure (Include in Part B Application, pp. 1290-91) (Notification of Intent)
3. History of Construction, Plant Hammond Ash Pond 3 (AP-3), Stantec (Part B Application, pp. 1257-75) (History of Construction).
4. Liner Design Criteria, Plant Hammond Ash Pond 3 (AP-3), Stantec (Part B Application, p. 1279) (Liner Design Criteria).
5. Location Restriction Demonstration, Unstable Areas, Plant Hammond Ash Pond 3 (AP-3) (Location Restriction Unstable Areas).
6. Report of Safety Assessment, Coal Combustion Surface Impoundments, Plant Hammond, AMEC Earth & Environmental, Inc., December 2010 (2010 Safety Assessment).
7. Various scientific literature sources, as indicated in the reference list at the end.

3. Professional Qualifications

I am a hydrogeologist with 40 years of broad professional experience in landscape and aquifer systems but with an emphasis in karst regions throughout the US and world. I earned degrees (BS Geology, 1984 and MS Geography, 1987) from Western Kentucky University (WKU) and a PhD in Environmental Science from the University of Virginia (Geology track) in 1993. Research for both graduate degrees focused on karst hydrogeology and a series of papers from my PhD dissertation *Early Development of Karst Systems* published in *Water Resources Research* has been collectively cited more than 400 times.

I currently serve as University Distinguished Professor of Hydrogeology at WKU, where I have written or coauthored 35 peer-reviewed journal papers or book chapters, more than 75 conference proceedings, papers, and technical reports, as well as given presentations at more than 150 regional, national or international scientific conferences and seminars. Much of this work was based on karst research and resulted in papers published in the leading professional water-related journals including *Journal of Hydrology*, *Groundwater*, *Water Resources Research,* and *Hydrogeology Journal* and leading geomorphology journals including *Earth*

Surface Processes and Landforms and *Geomorphology.* I have served as an Associate Editor for the *Journal of Hydrology, Hydrogeology Journal,* and the *Journal of Cave and Karst Studies* and am a Fellow, former Director, and past President of the Cave Research Foundation. At the invitation of the Springer Publishing Company, I am currently under contact and writing a new book *Applied Karst Hydrogeology* due in 2023. In recent awards I was the 2020 winner of the William Barfield Award for Outstanding Contributions in Water Resources Research from The Kentucky Water Resources Research Institute, and in 2021 the Western Kentucky University Faculty Award for Outstanding Research and Creative Activity.

I have Professional Geologist licenses in Kentucky, Tennessee, and Virginia. I have applied for reciprocal registration in Georgia, which (according to Rule 265-5-.01.(3).(b)) allows me to practice geology in the state for up to 90 days per year until my application is approved.

I have been responsible for karst-focused research, service, and training programs under contracts, grants or other cooperative efforts for federal agencies that include the Bureau of Land Management, National Park Service, US Department of Agriculture, US Environmental Protection Agency, US Forest Service, US Department of Energy, US Army Corps of Engineers, the US Agency for International Development, and the US Department of State.

Internationally, I am an invited member of the International Association of Hydrogeologists' Karst Commission as well as the Board of Governors of the International Research Center on Karst Under the Auspices of the United Nations Educational, Scientific and Cultural Organization (UNESCO) in Guilin, China. Since 1995 I have led or co-led four karst-focused United Nations scientific programs within the UNESCO International Geoscience Program. This work has included cave and karst fieldwork in 25 countries. For the past several decades I have been especially active in research into karst hydrogeology and water resources in the great karst region of southwestern China, home to some 80 million mostly rural Chinese. In 2019 I was awarded medals from both the China Geological Survey and the Guangxi Autonomous Region for 25 years of research in karst hydrogeology and water resources in China; two years before that China's President Xi Jinping personally awarded me the *International Cooperation in Science and Technology Award of the People's Republic of China*. This is China's highest award for foreign scientists, awarded in this case for "great contributions to China's hydrogeology and karst geology fields."

4. Background on Karst Hydrogeology

Hydrogeology refers to the science of how underground water is distributed and moves through the soil (as soil water) and rocks (as groundwater) beneath the surface. It is also concerned with the quality of that water and how its chemical composition is impacted by interactions with rocks, gasses, biological processes, surface waters, and human sources of contamination. Bodies of rock that can contain and transmit significant quantities of water are called *aquifers*, and the distribution and movement of groundwater within an aquifer is in turn governed by the types of rock through which it flows, as well as the nature and geometry of the spaces within the rock that give the water a place to reside and move. These interconnected networks of spaces might be spaces between sand grains, fractures, or in particularly soluble rocks like limestone, can be relatively large conduits or even caves large enough for humans to move through.

The surface topography also influences directions and rates of groundwater movement. Like surface water, groundwater tends to move from areas of higher elevations toward lower elevation, typically toward the nearest river. Climate also comes into play, as rainfall landing on the surface and infiltrating the ground is the source of groundwater in Georgia. Though groundwater is typically hidden underground and not directly visible, much can be inferred about the movement of groundwater by evaluating the factors described above that could collectively be called the hydrogeologic setting.

Karst landscapes and their associated aquifers are formed in especially soluble rocks, most commonly limestone and to a lesser extent dolomite, and in them features such as caves, underground rivers, and large springs can be common. Because of the high permeability of well-developed karst aquifers, meaning that because of the "Swiss cheese" character of the dissolved-out bedrock in many settings, water is able to pass relatively quickly and easily through these landscape/aquifer systems. This creates the possibility for several, interrelated environmental problems. First, rainfall can infiltrate easily into the ground and can carry along contaminants with which it comes into contact. These can then move quickly through the aquifer with little filtration or other processes that can ameliorate contamination. Karst aquifers and groundwater are, therefore, highly vulnerable to contamination.

It is necessary to define two critical terms—in order to understand key details of this report—that describe the behavior of groundwater flow related to the geometry of the spaces in the otherwise solid bedrock through which the water flows. These are *homogeneity* (or *heterogeneity*, the lack thereof) and *hydraulic conductivity* (Freeze and Cherry 1979). Homogeneity refers to how uniform the geometry and properties of those spaces are in different parts of the aquifer. If one considers water in a bucket of saturated sand, for example, in which the sand grains are of uniform size and shape, the sizes, shapes, and distribution of the interconnect spaces between the various grains are similar throughout the saturated material, and this would be considered to be a very homogenous system. Limestone karst aquifers are typically very different—often highly heterogeneous where the available spaces for water to exist and flow are highly variable in size and orientation. This means the properties of the rock, including how easily the rock can transmit water, are highly dependent on exactly where in the aquifer the rock is sampled. Hydraulic conductivity of the material in an aquifer quantitatively describes its permeability, or how easily water is able to move through the rock. These concepts are related in the sense that in a homogeneous aquifer the values of hydraulic conductivity are relatively uniform in space, meaning that the water is able to flow through material more or less with the same ease throughout different parts of the aquifer. In more heterogeneous aquifers, water can flow relatively easily in some areas of the rock, but with great difficulty, or not at all, in others. We will come back to these ideas below.

Because there are often voids in the bedrock of karst landscapes, this also create the potential for the ground surface to collapse into them. This can happen in several ways. In some cases cave passages and rooms themselves can cave in with the loss of structural support above, although this is generally rare. More commonly, soil above the bedrock can be washed down into the voids below the bedrock, leaving cavities in the soil which in turn can then collapse in what is often termed a *cover collapse sinkhole* (Figure 1).

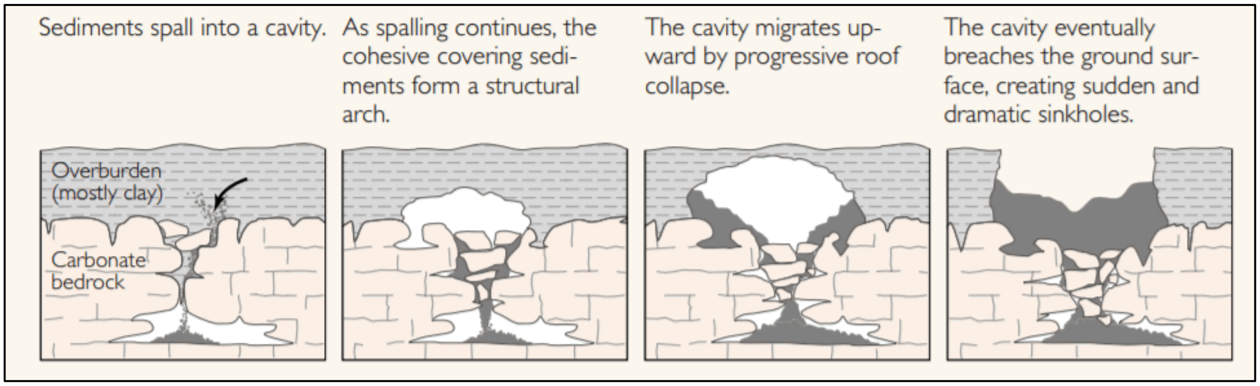


Figure 1. Sequence of events leading to the development of a cover collapse sinkhole (Galloway et al., 1999).

In other cases, material moving into subsurface voids can cause support to be lost from the bottom, creating a subsidence sinkhole (Figure 2). In both cases, ground subsidence can create structural problems through loss of support for buildings, roads, and other structures.

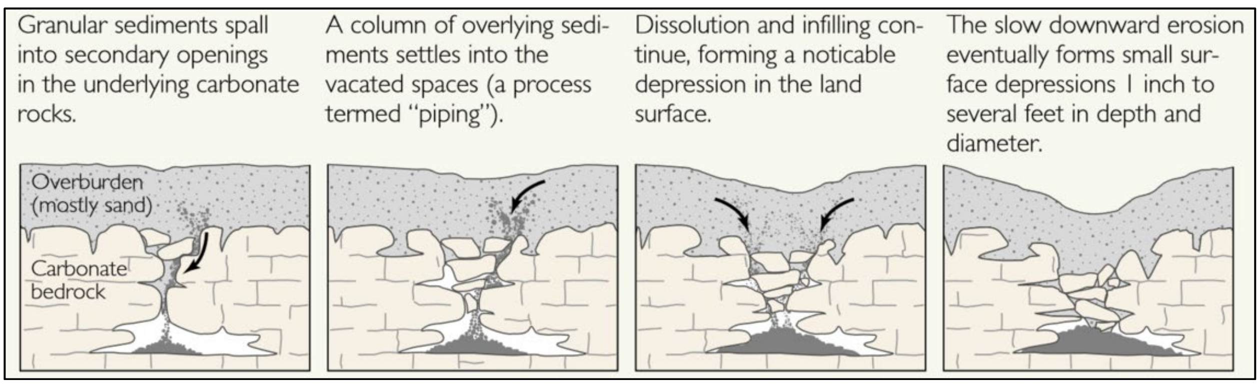


Figure 2. Sequence of events leading to development of a subsidence sinkhole, where support is lost from the bottom (Galloway et al., 1999).

If such subsidence or collapse occurs beneath structures containing potential contaminants, an unlined CCR storage pond, for example, or a lined pond whose liner could be torn or ripped in the event of an underlying collapse, both can also lead to the contamination of groundwater beneath the facility. This is exactly what occurred at AP-3 on July 20, 1977, when a sinkhole formed in the center of AP-3 about one month after the pond was first activated, after which one million gallons of CCR were lost each day into the groundwater of the karst aquifer beneath Plant Hammond (2010 Safety Assessment). Another occurred beneath AP-3 in 1979. These events demonstrate that there are continuous networks of karst conduits beneath the site to be able to allow such a vast amount of CCR to drain downwards through the karst aquifer.

5. Karst Hydrogeology at AP-3

5.1 The Conasauga Limestone Lies Beneath AP-3

AP-3 is situated on the Cambrian-aged Conasauga Formation (Figure 3). The rocks of this geologic formation mostly consist of shale, dolomite, and limetone (Cressler, 1970) and the bedrock beneath AP-3 (underlying successive zones of soil fill, river terrace alluvium, and highly weathered/fractured limestone) is dominated by limestone. According to the AP-3 permit application (Part B Application pdf p. 17-18):

> The limestone bedrock encountered during the Geosyntec field investigation was very similar in composition and texture between borings. Infrequently the limestone had a more massive appearance, but most of the limestone was medium to dark gray with a slabby or flaggy habit when broken in pieces by the sonic drilling. The limestone was very finely laminated with lighter and darker gray layers and contained interbeds of calcareous shale.

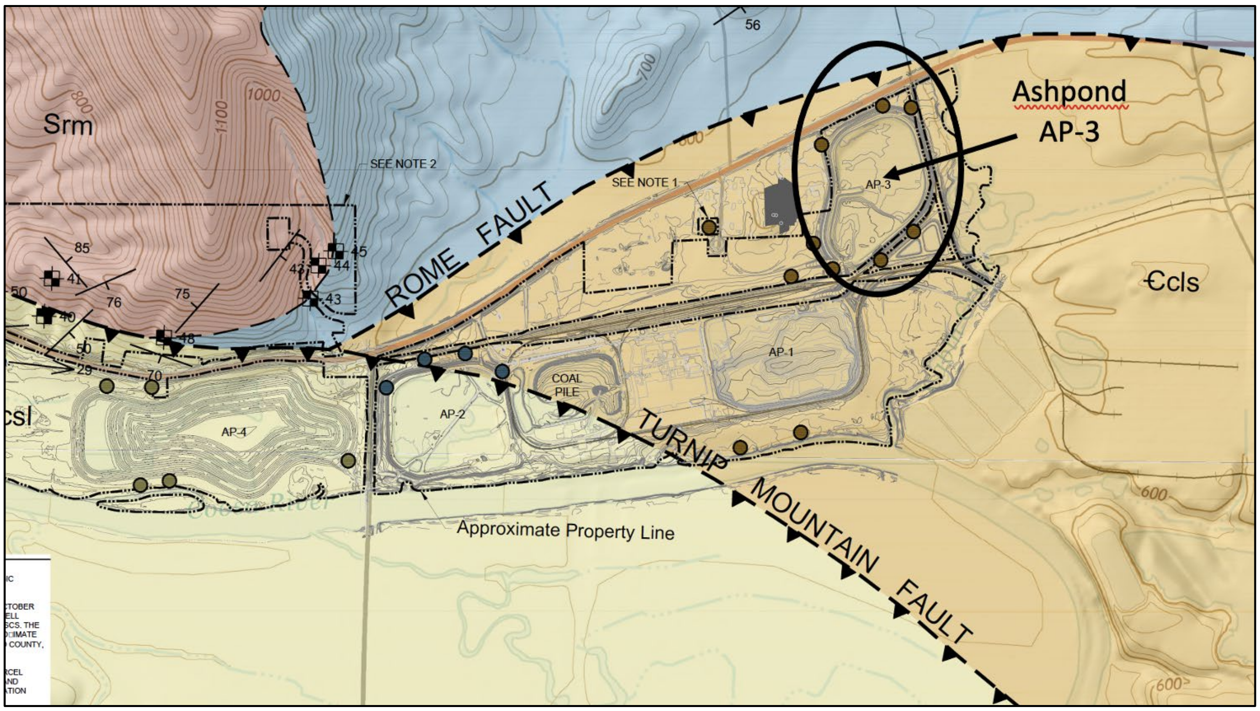


Figure 3. Geologic map of the Plant Hammond area (Part B Application pdf p. 41). The different colors correspond to different types of bedrock, and the tan colored area to the eastern side indicates the Conasauga formation, here mostly limestone.

The composition of the rock and other properties within the Conasauga formation, including the purity of the limestone where it exists (Cressler, 1970), are highly variable in different parts of Floyd County, including the propensity of the limestone to form karst aquifers. McLemore et al. (1999) for example, noted that

> Before proceeding further, it is important to remember that not all carbonate aquifers are karstic … Further, in the more topographically rugged portions of northwest Georgia, such as where carbonates of the Conasauga Group crop out on hill slopes south of Vans Valley in Floyd County, fractures are "tight" and solutional enlargement is nil (Golder

Associates, 1996). Here there is minimal void space into which surficial soils can be "eroded" and true karstic conditions do not exist.

However, as I discuss below, based on several consistent lines of evidence, well-developed karst aquifer does exist within the Conasauga Limestone beneath AP-3.

5.2 There are Many Voids from Dissolution of the Conasauga Limestone Beneath Plant Hammond

Although it is true that at the resolution of the topographic maps (Part B Application pdf p. 31) shown for the sites there is no apparent expression of surface karst features, the subsurface investigations show *extensive* dissolution of the limestone beneath the site. Boring Z-17 in the 1977 sketch below (Figure 4) was made prior to AP-3 becoming operational, and shows several voids (the white spaces indicated at the bottom of the drawing indicate voids or space rather than solid rock) that were encountered in the bedrock. Although the boring log from Z-17 in the drawing (and thus the date it was drilled) is missing from the Part B Application, the logs from the Z-series borings that are included, including Z-16 to the left Z-18 to the right, were made in December 1976 and January 1977, several months before AP-3 became operational (Part B Application, pdf pp. 104-112). The planners knew there were voids in the limestone beneath AP-3 *before* CCR disposal was initiated.

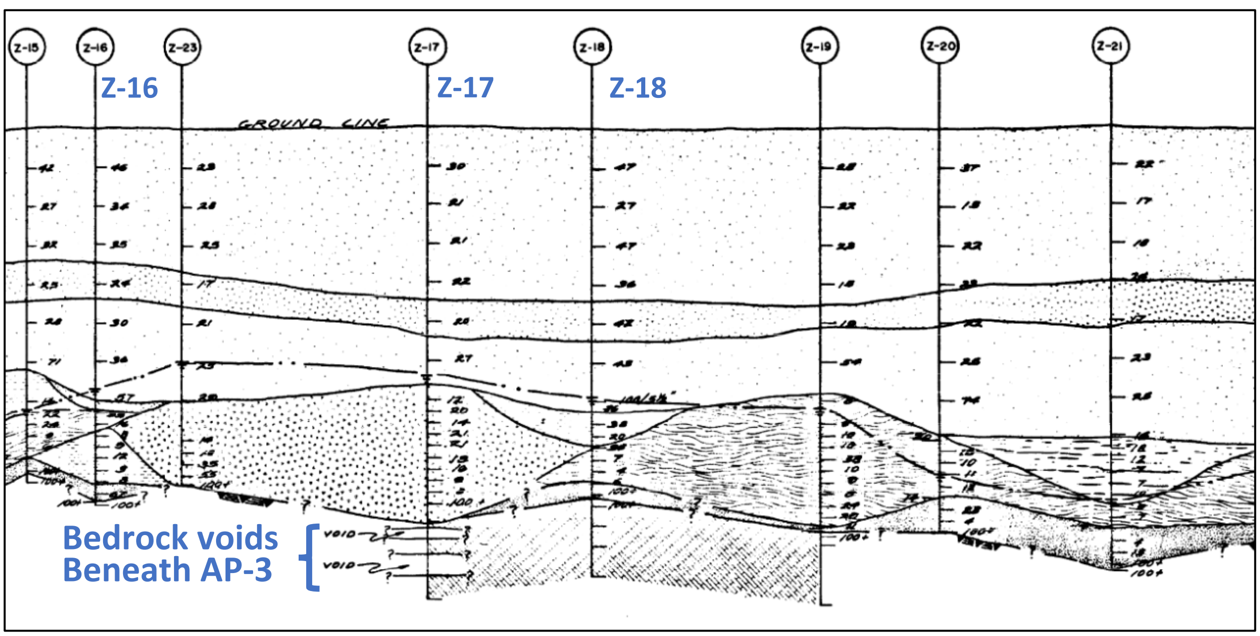
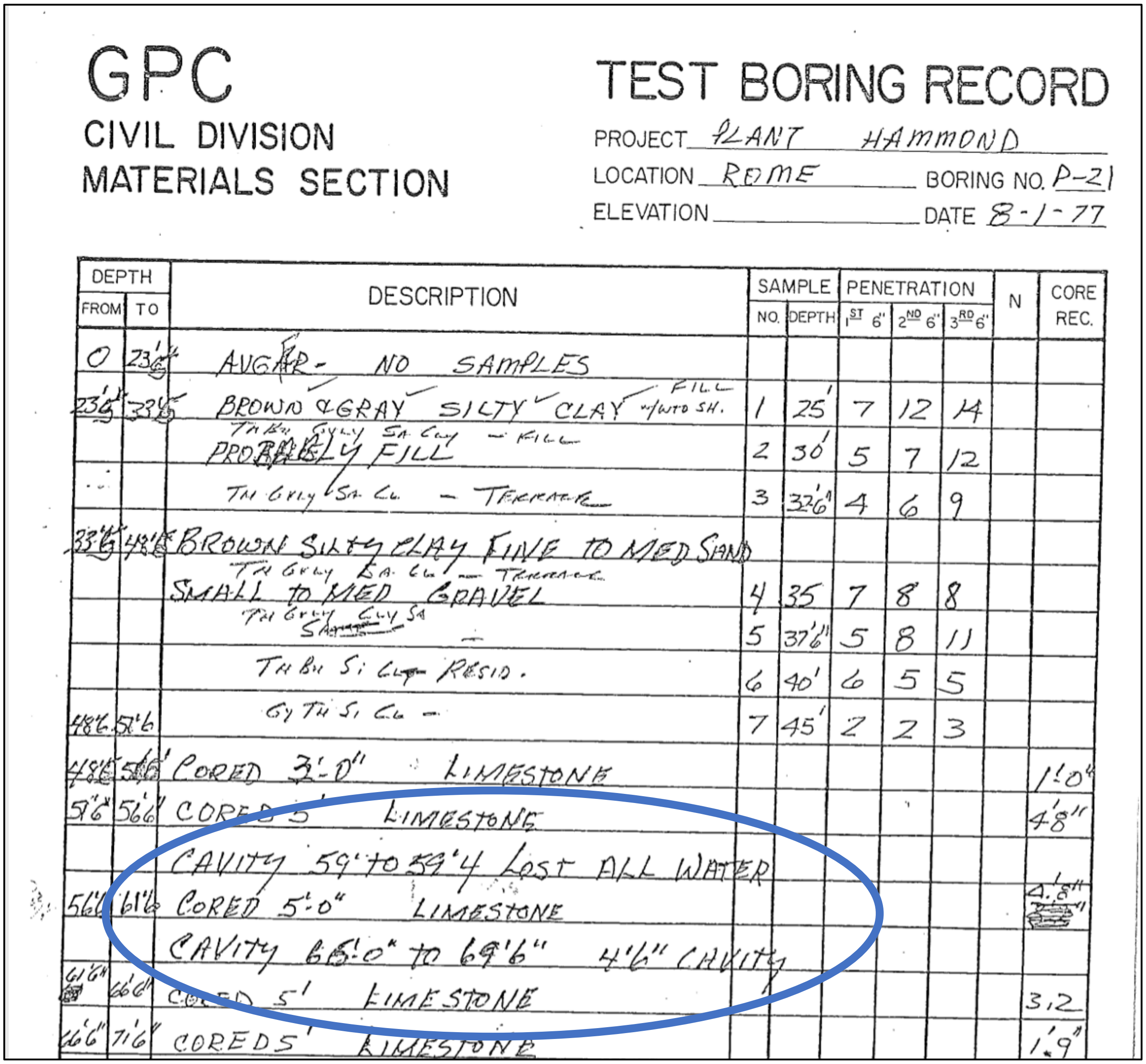


Figure 4. 1977 sketch of borings through the CCR from and underlying material, showing voids (the white spaces indicated are voids, or empty spaces the otherwise solid bedrock) in the beneath the pond that have formed from limestone dissolution that were known before AP-3 was initiated. This diagram, though not labeled, is apparently from the 1976-77 Georgia Power Company (GPC) investigation.

Another round of subsurface investigation followed in August 1977, based on drill logs by GPC Civil Division Materials Section (Part B Application, pdf p. 99 and p. 102-103), with more voids encountered, as shown for example below in Figure 5.


GPC
CIVIL DIVISION
MATERIALS SECTION

TEST BORING RECORD

PROJECT PLANT HAMMOND
LOCATION ROME BORING NO. P-21
ELEVATION DATE 8-1-77

DEPTH FROM	DEPTH TO	DESCRIPTION	SAMPLE NO.	SAMPLE DEPTH	PENETRATION 1ST 6"	PENETRATION 2ND 6"	PENETRATION 3RD 6"	N	CORE REC.
0	23'6"	AUGAR - NO SAMPLES							
23'6"	33'6"	BROWN & GRAY SILTY CLAY FILL w/ WTD SH.	1	25'	7	12	14		
		Tn Bn Gray Sa Cly - FILL PROBABLY FILL	2	30'	5	7	12		
		Tn Gray Sa. Cl. - TERRACE	3	32'6"	4	6	9		
33'6"	48'6"	BROWN SILTY CLAY FINE TO MED SAND							
		Tn Gray Sa. Cl. - TERRACE SMALL TO MED GRAVEL	4	35	7	8	8		
		Tn Gray Cly Sa	5	37'6"	5	8	11		
		Tn Bn Si Clay RESID.	6	40'	6	5	5		
48'6	51'6	Gy Tn Si Cl -	7	45'	2	2	3		
48'6	51'6	CORED 3'-0" LIMESTONE							1'0"
51'6"	56'6"	CORED 5' LIMESTONE							4'8"
		CAVITY 59' TO 59'4 LOST ALL WATER							
56'6"	61'6"	CORED 5'-0" LIMESTONE							4'8"
		CAVITY 65'-0" TO 69'6" 4'6" CAVITY							
61'6"	66'6"	CORED 5' LIMESTONE							3.2
66'6"	71'6"	CORED 5' LIMESTONE							1'9"

Figure 5. Drilling record of Boring P21 (Part B Application pdf p. 102). Even though the higher void is smaller, less than a foot tall, it is critically important to note that when this void was encountered, the drillers "lost all water." The importance of this is described in the text.

In borehole P-21 a void less than a foot tall was encountered (Figure 5), followed by 5 feet of solid rock and then another larger void below that. Though the higher one was smaller, it is critical to note that when that void was encountered, the drillers "lost all water." In this style of drilling a type of "drilling fluid" is injected down the drill pipe or "stem" to the end where the bit is drilling downward into the rock, with the fluid cooling and lubricating the bit. This drilling fluid is under pressure, and if a void is encountered when drilling, the drillers can "lose water." When that happens, the well has intersected the interconnected conduit system of the karst aquifer, and the drilling fluid is draining away into the aquifer. It is this very efficiency with which the conduit system can carry away the fluid through otherwise solid rock that makes karst aquifers so vulnerable to contamination. Loss of drilling water is a characteristic feature of well-developed karst aquifers

By October 1977, a report was submitted by Law Engineering (LETCO, 1977) (not available for review, but based on several indirect sources including a description in the 2010 Safety Assessment) that also indicated the presence of voids beneath AP-3 (2010 Safety Assessment pdf. p. 9) clarifying that these were open with no fill material:

> The investigation also reported that solution cavities were penetrated by several borings. Cavities "up to 3.5 feet thick" occurred within the "upper 20 feet of rock" on the east side of the ash pond, while cavities on the north and west sides "ranged from 0.8 to 2.8 feet thick" and occurred in the upper 10 feet of rock. At the time, "all of the cavities penetrated were open, with no filling material."

Additional drilling in the vicinity of AP-3 was also done in 2017 as shown in Figure 6 and Table 1, below. In the log for Boring AP-3 B10 (Figure 6), one can see that like earlier wells, several voids were encountered, and the drilling fluid was lost, here described as a "loss of circulation" on Figure 6. "No recovery" in Figure 6 simply means that no rock was found in that interval, just empty space.

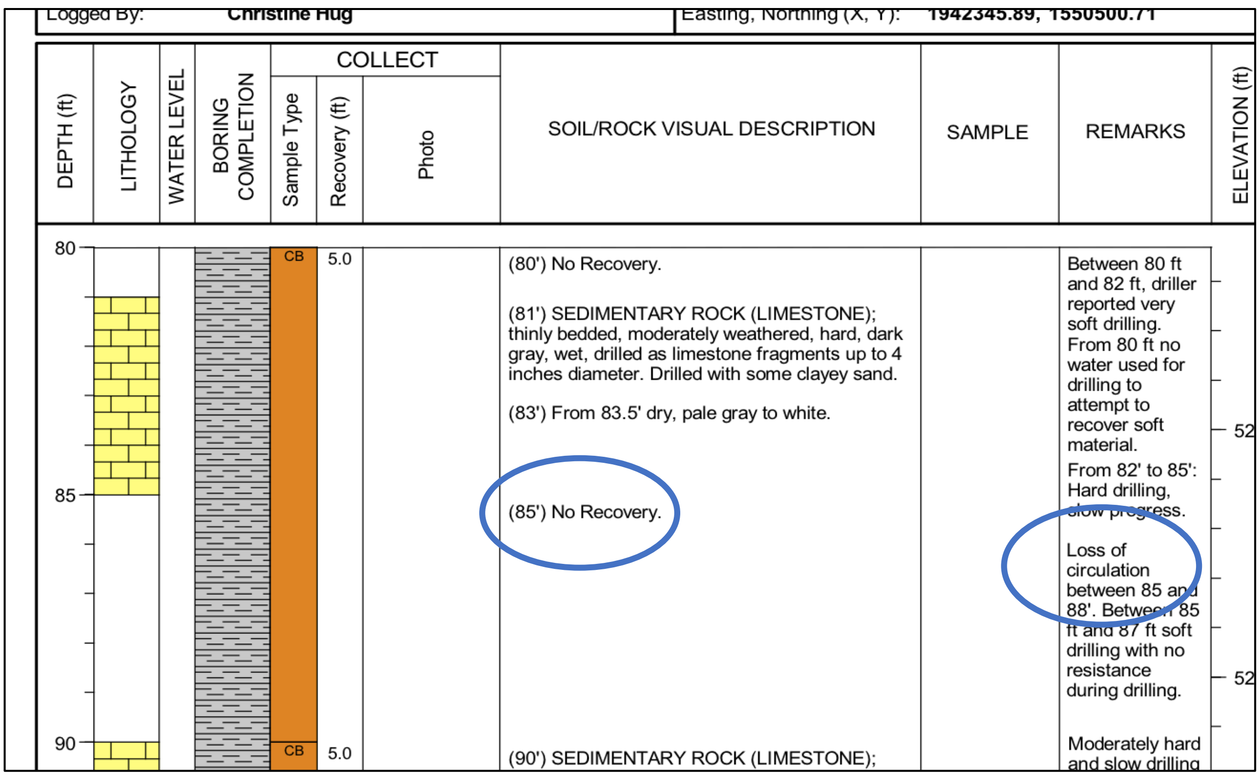


Figure 6. Drilling log for Boring P3-B-10. The yellow brickwork pattern indicates limestone bedrock, and the white zones are voids (Georgia Power, 2018 pdf p. 85). "No recovery" means that there was no rock present in that interval and "loss of circulation" is another way to say that the drilling fluids drained away into the underground network of karst conduits.

In addition, Table 1 shows a summary of the borings that had voids, including AP-3 B9 with a remarkable *30 feet* of void space. The other notation shown is where the "drilling rod dropped down" in several boreholes. This is where the bottom end of the drill falls down into a void

Borehole	Number of voids	Void interval*	Void height	comments
AP3 B4	1	~60'-61'	<1'	drilling rod dropped down, drilling water lost
AP3 B7	1	60'-65'	5'	
AP3 B9	2	60'-70'	10'	drilling rod dropped down, drilling water lost
		75'-95'	20'	drilled through void with soft material
AP3 B10	2	75'-81'	6'	drilled through void with soft material
		85'-90'	5'	no rock recovered, drilling water lost
AP3 B11	2	55'-60'	5'	in weathered limestone, no rock recovered
		75'-76'	1'	drilling rod dropped down, drilling water lost
P21	2	59'-59'4'	4" or 0.4'	drilling water lost
		65'-69'6"	4'6"	
Z18-B	Multiple	47.3'-57.3'		40% of rock not recovered over several voids
HGWC 121A	1	30'-35'	5'	no recovery
*values are feet below the ground surface				

Table 1. In a clear sign of extensive karst aquifer development, numerous bedrock voids are found in the bedrock beneath Plant Hammond in the vicinity of AP-3 as much as 20 feet tall, in the limestone bedrock.

under the influence of gravity. This can not only be a cause of great annoyance for drillers in karst aquifers because the very expensive drilling steel can be broken or even lost down the hole, but is a characteristic sign of a well-developed karst aquifer.

5.3 Sinkholes Beneath AP-3

5.3.1 1977 Sinkhole Collapse and Aquifer Contamination

One month after initiation of CCR disposal in June, 1977, on July 20 a major loss of CCR, estimated at one million gallons per day, occurred with the development of a sinkhole beneath AP-3 (Figures 7 and 8). This event was described as follows, the euphemistic term "seepage" notwithstanding (2010 Safety Assessment):

> Filling of Ash Pond #3 began in June 1977, and was terminated on July 20, 1977 due to high piezometer levels and seepage along the toe of the west side of the dike. Water was seeping into a concrete trench and was ponding on the adjacent church property. As a result of the seepage, a subsurface investigation was performed by Law Engineering to determine the source of the seepage. Law Engineering indicated that approximately 1 million gallons per day was leaking from Ash Pond No. 3. Further, the report state [sic] the removal of the relatively impermeable material overlying the jointed bedrock had allowed water to move from the pond. Additionally, low to very high permeability measurement in materials below the dike, including solution cavities were encountered during coring operations.

Not only does this show that a major, well developed karst aquifer lies beneath AP-3, but also the seepage represented a major groundwater contamination of CCR into this aquifer, any

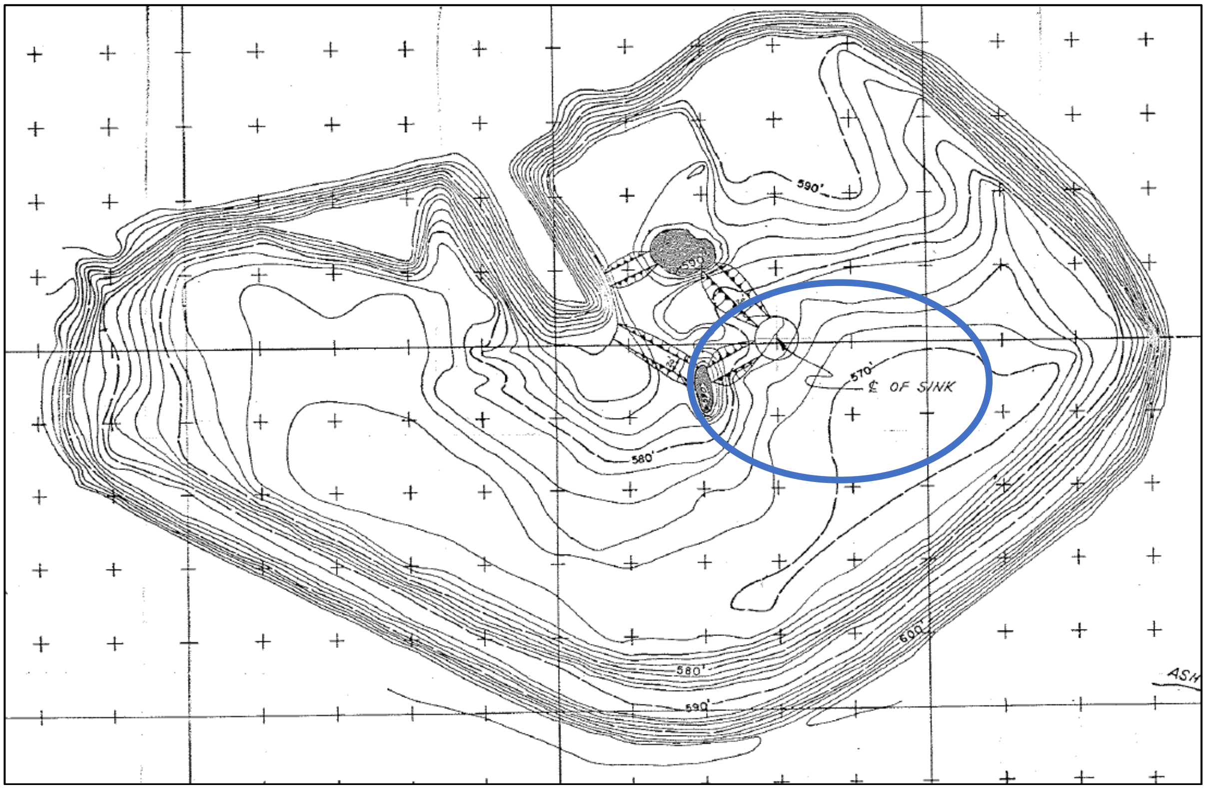


Figure 7. topographic map of AP-3 from a drawing dated November, 1979 (Part B Application pdf p. 1272). Showing the of location of a sinkhole. Added blue circle highlights the area of sinkhole.

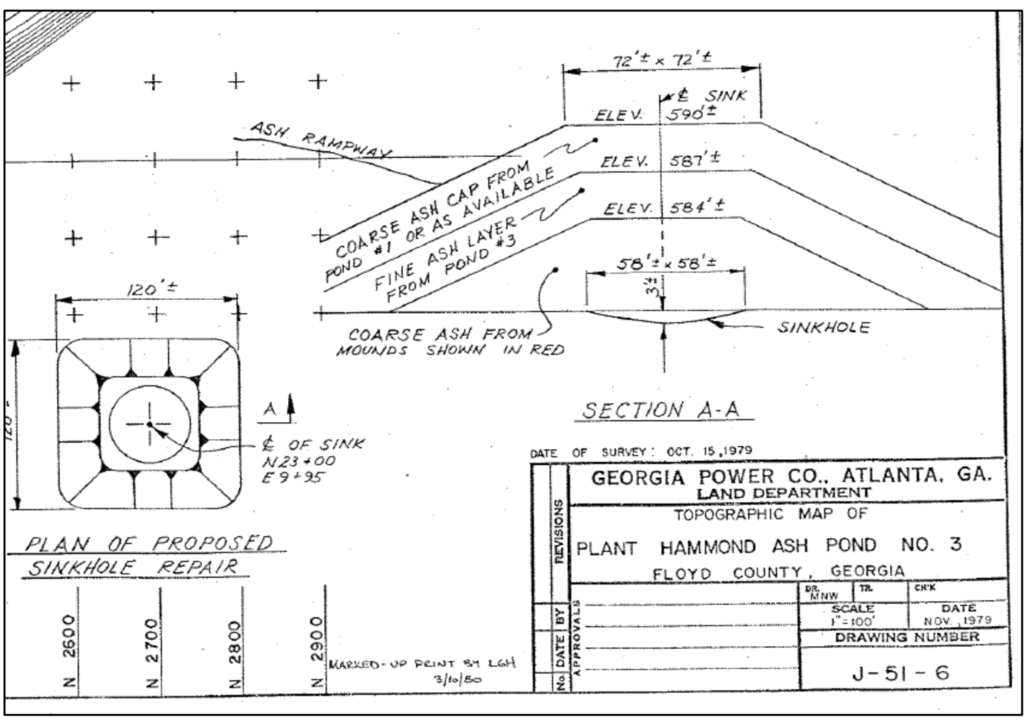


Figure 8. Details of proposed sinkhole repair for the same drawing as that from Figure 7 Indicating that the sinkhole was 58 feet in diameter (Part B Application, pdf p. 1272).

mention of which was omitted from the application. In addition, the 2010 Safety Assessment noted that "low to very high permeability measurement in materials below the dike, including solution cavities were encountered during coring operations." In considering this statement, recall the discussion of aquifer homogeneity (or more importantly heterogeneity) above on p. 2

> in a homogeneous aquifer the values of hydraulic conductivity are relatively uniform in space, meaning that the water is able to flow through material more less with the same ease throughout different parts of the aquifer. In more heterogeneous aquifers water can flow relatively easily in some areas of the rock, but with great difficulty or not at all in others.

A classic characteristic of well-developed karst aquifers is that they typically have extreme heterogeneity, a condition very well captured by the description of the bedrock beneath AP-3 in the 2010 Safety Assessment. We will return to this idea once more.

5.3.2 1979 Sinkhole Beneath AP-3

Although the Part B Application narrative fails to mention the existence of any sinkholes under AP-3, over 1,200 pages into the document a November 1979, annotated March 10, 1980 diagram shows plans for repair of a large (58 feet across) sinkhokle. While records (2010 Safety Assessment) indicate that after the 1977 sinkhole at AP-3 was returned to service in October 1977, this 1979 diagram is labeled as a "Plan of *Proposed* Sinkhole Repair*"* (emphasis added). Therefore, this appears to be a second *major instability* event at AP-3.

This is consistent with the narrative from the 2010 Safety Assessment (pdf p. 62) which states that "An interoffice memo dated March 14, 1980, indicate a sinkhole investigation at Ash Pond No. 3 was performed and recommendations were submitted." This date, four days after the hand written date in Figure 8, makes it appear that these refer to the same feature.

5.4 Conclusion on Karst Hydrogeology at AP-3

The presence of numerous, in places large, voids in the Conasauga Limestone, at least two large sinkhole collapse events beneath AP-3, the frequent loss of drilling water, and the fact that the ends of the drill bits dropped into empty spaces where the solid rock was missing, are all quintessential features of well-developed karst aquifers.

It is simply wrong for Georgia Power to call Conasauga Limestone "unweathered limestone". One of the principal weathering processes is dissolution of rock by water, and there has been extensive dissolution of the Cansauga limestone, leading to the extensive subsurface networks that have been abundantly documented by the data in the application I have described in Sections 5.2 and 5.3.

6. Hydrogeologic Characterization in the *Permit Application (Part B) AP-3 Inactive Surface Impoundment Plant Hammond Floyd County Georgia*

An analysis of Georgia Power's permit application shows that the integrity of the relevant hydrogeologic characterization has been compromised through omission, unsupported claims, and incorrect analyses. The data themselves, with great consistency, show that an extensive underground karst drainage system underlies Plant Hammond, including AP-3 and yet the application seems to ignore, downplay and draw attention away from this fundamental conclusion.

6.1 Omission of Sinkhole-Related Structural Instability Events

A clear way to identify such problems is to identify contradictions. Perhaps the most egregious example is the section below from the Stantec *History of Construction* (Application Part B pdf. p. 1260):

> (xii) Known record of structural instability:
>
> AP-3 was placed into operation in June 1977. In July 1977, seepage was identified in the concrete drainage ditch along the toe of the west downstream slope. AP-3 was taken out of service and an investigation was initiated in August 1977 to determine the cause of the seepage. In October 1977, actions were undertaken to address the issue, and following the repair, AP-3 was placed back in operation in October 1977. AP-3 was ultimately converted to a dry ash disposal area in the early 1980s. No dike stability issues were observed as a result of this seepage. *No structural instability issues have been observed for AP-3.*

(Emphasis added) While concluding that "No structural instability issues have been observed for AP-3"*, this completely omits the facts (2010 Safety Assessment) that a subsurface investigation determined that a sinkhole had opened up directly beneath the ash pond and that some one million gallons a day were lost downward into the karst aquifer below AP-3*. This astounding omission clearly gives the impression that there was simply seepage through the dike that was repaired, which is obviously misleading.

Records also indicate that another large sinkhole, 58 feet in diameter, opened up beneath AP-3 and was remediated, possibly, in 1979-80.

Indeed, although these structural instabilities may perhaps have been the motivation for the facility to switch operations to dry-ash handling, discussion of these collapse events *were wholly omitted from the narrative of the application.* Indeed, the only indication that this had ever happened at all shows up on diagram, included in the application without explanation, more than 1,200 pages into the document.

6.2 Mischaracterization of the Hydrogeology of the Conasauga Limetone is Based on Flawed Analysis of Hydraulic Conductivity/Permeability Data

If we consider the data presented in the Plan B Application for the site there appears to be a single, *nearly* consistent interpretation of the hydrogeologic data: the fact that at least two major sinkholes appear to have developed under AP-3, the numerous and in some cases very large voids that have been encountered, the loss of drilling water when drills have intersected the underground drainage network, and the voids into which the drilling steel has dropped down into empty spaces rather than bedrock all clearly indicate a highly developed karst aquifer system beneath AP-3.

6.2.1 Example of Flawed Analysis of Hydraulic Conductivity/Permeability Data

Why say that this appears to be a *nearly* consistent story? In reality, it is indeed a *fully* consistent story: This is a well-developed karst aquifer. As explained below, however, due to Georgia Power's mischaracterization or incorrect interpretation of hydraulic conductivity data, they conclude this is not a well-developed karst aquifer.

So, we circle back around once again to the ideas of *permeability* and *hydraulic conductivity,* which let's just shorten and call *conductivity*, with a reminder that both of these terms are used more or less interchangeably to describe how easily the groundwater can move through the spaces in a particular location in the otherwise solid rock. And as a reminder, we have already seen that the bedrock aquifer beneath the site (like many karst aquifers) is highly *heterogeneous*—the conductivity or permeability is highly variable in different parts of the rock, so that water can move very easily through some areas of the rock and hardly at all in other areas.

While it is the mischaracterization of the data from the solid limestone beneath AP-3 that is most serious, I'll start with an easier-to-follow example of this error from the data for a layer of "residuum," which is a name for the residual soil above the bedrock. A common technique, employed here, is to measure the conductivity or permeability at different places throughout a layer, in this example the residuum layer. Then, an average of those values can be used as a single value to characterize the layer's overall conductivity or permeability, to describe how easily the water moves through that layer in general. While in this explanation the actual values themselves are not important, nor how conductivity is measured, it is *key* to note that layers with high conductivity or permeability values, through which water can move very easily, can also transport contaminants more easily than lower conductivity materials. So, under an unlined waste pond, for example, the lower the values of conductivity the better the rocks should be able to contain the waste.

For an example of how this has been done at AP-3, Table 2 shows the actual permeability measurements for the 1977 Law Engineering report (Part B Application pdf p. 138), including nine from the residuum. Without focusing on the details of the individual values themselves, we can generalize that these are relatively tiny numbers (as shown in scientific notation), and so relatively low permeability values (Freeze and Cherry, p. 29), remembering that low is good in this context. We can then look at the summary table (Table 3) for these measurements along with later ones, and although in this table these values are expressed as hydraulic conductivities with different units than those of Table 2, coincidentally the chosen units give closely comparable values (Freeze and Cherry, p. 29). We see that the highlighted mean, or average, of these residuum values is a similarly small number, indicating relatively low overall hydraulic conductivity for this layer in general.

FIELD PERMEABILITY MEASUREMENTS

Piez. No.	Permeability (Ft/Min)	Material Tested
P-1u	2.0×10^{-5}	Fill
P-3u	1.2×10^{-5}	Fill
P-11	1.0×10^{-5}	Fill
P-14	2.6×10^{-6}	Fill
P-17	1.0×10^{-5}	Fill
P-19	1.6×10^{-5}	Fill
P-20	2.3×10^{-6}	Fill
P-23	1.5×10^{-6}	Fill
P-1L	2.0×10^{-4}	Residuum on rock
P-3L	2.4×10^{-5}	Residuum on rock
P-4	*	Residuum on rock
P-5L	3.3×10^{-4}	Residuum on rock
P-6	7.1×10^{-4}	Residuum on rock
P-15	8.3×10^{-4}	Residuum on rock
P-18	1.1×10^{-4}	Residuum on rock
Z-16	1.2×10^{-6}	Residuum on rock
Z-21	2.7×10^{-4}	Residuum on rock
P-10	5.1×10^{-4}	Terrace
P-13	1.0×10^{-4}	Terrace
P-16	8.4×10^{-5}	Terrace (+ some residuum
P-22	7.4×10^{-4}	Terrace
P-4A	4.2×10^{-3}	Rock (+ some residuum)
P-9	1.0×10^{-4}	Rock (+ some residuum)
P-12	**	Rock (+ some residuum)
P-21	$7^{+} \times 10^{-4}$	Rock (+ some residuum)

* Permeability in P-4 was too high to measure with available equipment.

** There was no response in P-12, apparently due to clogging the piezometer with grout during the sealing process.

Source: Investigation of Water Loss, LETCO, October 1977.

Table 2. Measured hydraulic conductivity values of various subsurface layers from the 1977 Law Engineering report (Plan B Application pdf p. 138).

However, there is a real problem with this calculation. If we look more closely at Table 2 of the permeability measurements, we see that one of the residuum values is missing and instead there is an asterisk. The asterisk indicates that the "*Permeability in P-4 was too high to measure with available equipment.*" So, the calculation was based on the average of a bunch of small numbers, and instead of considering the effect of a very high number on the average*, **this relatively large measurement was ignored**, and no mention of this omission was noted. Ignoring well P-4 results in a reported mean substantially lower than the data actually indicate.*

6.2.2 Flawed Characterization of the Conasauga Limestone

Lithologic Unit	Range of K_h or K_v (cm/s)	Geometric Mean K_h or K_v (cm/s)
Horizontal Hydraulic Conductivity		
Ash	4.13×10^{-2}	4.13×10^{-2}
Fill	7.62×10^{-7} to 1.02×10^{-5}	3.33×10^{-6}
Terrace Alluvium	4.27×10^{-5} to 3.76×10^{-4}	2.14×10^{-4}
Residuum	6.10×10^{-7} to 3.57×10^{-3}	1.47×10^{-4}
Highly Weathered/Fractured Limestone	5.08×10^{-5} to 2.35×10^{-2}	9.76×10^{-4}
Unweathered Limestone	4.98×10^{-5} to 2.91×10^{-3}	4.46×10^{-4}
Vertical Hydraulic Conductivity		
Residuum	1.00×10^{-7} to 1.40×10^{-6}	2.91×10^{-7}

Table 3. Summary hydraulic conductivity values for the material beneath Plant Hammond, including the artificially low mean value for the residuum as explained the text (Part B Application pdf p. 27).

This same error occurs in the reporting of the conductivity of the Conasauga Limestone, with the same result that the reported mean is lower than what the data themselves clearly show. To explore this, we can consider the question of how hydrogeologists deal with values, like in well P-4 discussed above, with very high values of conductivity, which is what happens when a fracture or conduit is encountered, as in the numerous places where "drilling water was lost" at AP-C (Figure 9). Compared to the rock surrounding the fracture and conduits, the conductivity in such cases is typically so high it can be hard to measure, as discussed above for well P-4 in the Law Engineering Report. *Certainly, the answer is not to ignore these data*, as was done in Georgia Power's application.

There are two approaches taken by hydrogeologists, a theoretical one and a practical one. In the first, when a groundwater flow model is designed for a karst aquifer in which the model accounts for includes fractures, a standard procedure is to consider the fractures (typified in real world aquifers as places where drilling water is lost) as having *infinite* hydraulic conductivity (e.g. Gringarten et al. 1974 p. 374; Field, 1999 p. 163; Halihan 1999, p. 83; Maréchal et al. 2008, p. 13; Bailly-Comte et al. 2010, p. 57).

In the practical and much more common approach, it is recognized that like people, water flows along paths of least resistance, and it has been estimated through analysis of real karst aquifers that more than 90% of the flowing water can be transported through the fractures and conduits (Worthington et al., 2000, p. 465; Green et al. 2006 p. 163) and not the rock in between with dramatically lower ability to transmit fluids. In addition, White and White (2003, p. 1) estimated groundwater flow velocities in the highest permeability zones of a karst aquifer (the fractures and conduits) are often 1,000,000 to 10,000,000,000 times higher than in the lowest permeability zones (the rock between them). Generalizing, they wrote that in such aquifers there is

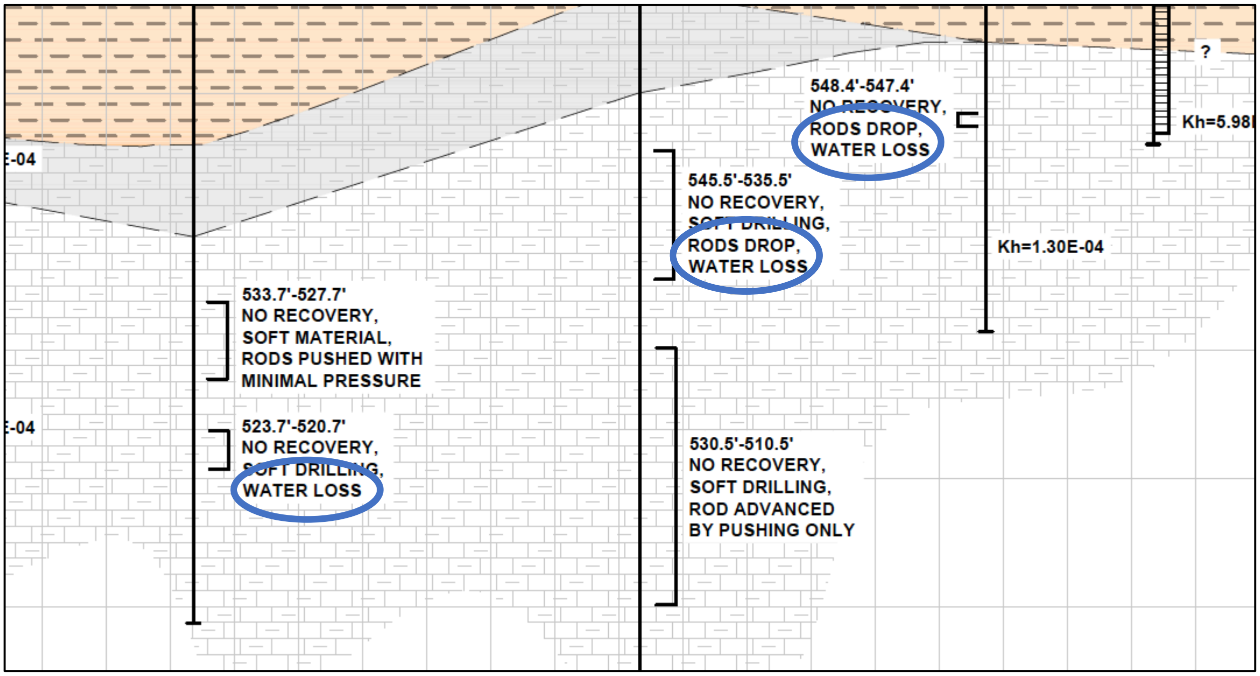


Figure 9. Part of an AP-3 cross section C-C' (Plan B Application pdf p. 35) showing three wells where drilling fluids were lost, highlighted in blue, draining away into the network of karst conduits that permeate the Conasauga Limestone beneath Plant Hammond. The hydraulic conductivity of such fractures is so much higher than the surrounding solid rock, it is generally assigned *infinite* values in numerical groundwater flow models (see references in text).

> a concentration of flow along a few preferred pathways. Flow velocities in conduits are often sufficient to drive the system into a turbulent regime. The contrast in velocity between the least permeable and most permeable parts of the same aquifer is often six to ten orders of magnitude. It is a common fallacy to assume that if one scales over a sufficient volume of the aquifer, *then the fractures and conduits will average out and the aquifer as a whole can again be characterized by a single hydraulic conductivity.* ***This does not work.***

(Emphasis added).

In summary, in thea karst aquifer, which has been abundantly documented *by the data* to exist in the Conasauga beneath Plant Hammond, while the low, reported hydraulic conductivity of 4.46 x 10^{-4} cm/s may be a fine value to characterize the relatively impermeable rock between the fractures and conduits of the Conasauga Limetone, that's not where the water is flowing and it therefore provides a misleading, and indeed meaningless, characterization of the flow through the aquifer as a whole.

7. Conclusions

7.1 Existing Hydrogeologic Analysis of the Part B Application

The presence of sinkholes, extensive networks of voids, and other documented characteristics of the Conasauga limestone beneath Plant Hammond in the vicinity of AP-3 indicate extensive karst development in the formation. Inconsistencies between the narrative of Georgia Power's Part B Application and the actual data in the application indicate that integrity of the relevant hydrogeologic characterization has been compromised through omission, unsupported claims, and incorrect analyses.

Sometimes errors or omissions are made, but an apparently common feature of those in the narrative of the application is to downplay the karst development. In any objective analysis of the hydrogeology of the site karst quickly presents itself as a central theme, yet in the 1,290 page application one finds the word karst used but twice (Part B Application pdf p. 18 and p. 1,260). In both cases, Georgia Power seems to claim that karst is really not an issue here, but when you take a closer look, this is patently false.

On page 18 there are three statements appearing to downplay the karstic nature of the bedrock beneath the site.

> 1. "Solution openings, likely formed by dissolution of the limestone along the bedding planes and joints, were observed in recent and previous investigations … Most of these features were noted in boring logs as filled with clay, mud, or other sediment."

While there are in fact both voids with sediment and empty voids—in the 1977 Law Engineering *Investigation of Water Loss* "all of the cavities penetrated were open, with no filling material" (2010 Safety Assessment pdf p. 9). The fact that there is sediment in some just emphasizes the connection between the surface materials and the karst network deeper in the aquifer.

> 2. "The caliper records indicate that the solution openings that are present do not typically extend more than several inches from the borehole."

In addition to the fact that no caliper data were provided in the application, that is simply not correct. The lost drill water in numerous voids proves these are part of a larger, integrated underground drainage network, or the water would have no place to go.

> 3. "Observation of rock cores during drilling and review of boring logs from the site indicate the presence of discontinuous solution features…"

This is incorrect. Both the major sinkhole incidents and the lost drilling water prove that these are continuous solution features, or the million gallons per day of CCR that poured underground in the summer of 1977, the material lost underground in the 1979 sinkhole incident, or the lost water from drilling at numerous places, would have nowhere to go.

> 4. "…but do not suggest the presence of large, laterally continuous karst features such as caverns or sinkholes."

As discussed above in points 3 and 4 above, they are in fact continuous, and voids do not have to be large "caverns" to effectively transmit water and contaminants. 10' and 20' voids, as shown in Well AP-3 B9 are in fact "large."

On page 1,260 of the Part B Application, the other place where karst is mentioned, Georgia Power makes two more statements:

> 1. Solution features on the order of a few inches up to almost one foot have been documented in some boreholes.

Although there are indeed such small voids, for this to imply that these are the only voids that were found is wring. Among numerous other larger ones, well AP3 B9 has two voids that are 10' or more feet tall.

> 2. A comparison of solution features between borings does not indicate laterally continuous karst features within the bedrock.

First, the 1977 and 1979 sinkholes, along with the loss of drill water at numerous locations prove that there are continuous karst features. In addition, it is unclear what comparison they are referring to that "do[es] not indicate laterally continuous karst features." Are they referring to the solution features not being the same size or the same elevation? Why should they be? Typically, such conduit networks have highly three-dimensional geometry (think of looking down into a bowl of noodles) and in general trying to tell whether voids in more than one well are part of the same conduits (or more to the point in this case that they are not) just based on their geometry just does not work. I am familiar with several methods through which connectivity of karst features *can* be established including tracer tests (Groves, 2007) and direct cave exploration and mapping (Jeannin, Groves, and Häuselmann, 2007). I once used a smoke-generating machine to see if two adjacent wells were connected, and in a famous example, in 1960 two west Virginia caves were connected through passages too small for humans when a strong, nauseating "skunk" oil was released in one cave and was smelled in the other (Dasher, 2001).

Based on the actual data presented by the boring logs in this application, there is nothing to support Georgia Power's conclusion that the data do "not indicate laterally continuous karst features within the bedrock."

Based on the evidence I have discussed above even the Site Conceptual Model Summary (Part B Application pdf p. 22), the most fundamental description of the hydrogeological conditions:

> Solution openings observed in borings at the Site likely formed by dissolution of limestone along the bedding planes and joints and are not laterally continuous. Due to the discrete and discontinuous nature of these solution features, linear preferential flow pathways for groundwater are not expected, but rather flow is along the highly weathered bedrock unit atop the underlying competent bedrock.

is unsupported by the groundwater investigation data in this application.

7.2 Potential Risks Associated With the Current Conditions at AP-3

An obvious question concerns the karst-related risks, with a focus on the potential for sinkhole collapse and groundwater contamination. Even though processes for CCR handing at AP-3 were switch to dry handing after the late 1970's sinkholes, and the cap overlying the waste may well prevent vertical infiltration over the footprint of the pond itself, in my opinion there are still indeed significant reasons for concern.

The first very clear conclusion is that this application has *not* shown that the current conditions with regard to karst environmental risks have been eliminated. For the very reasons I have stated earlier, inconsistencies between the narrative and the actual data in the application indicate that integrity of the relevant hydrogeologic characterization has been compromised through omission, unsupported claims, and incorrect analyses.

In my opinion any evaluation of impact of karst-related risks at the site would begin with an objective, thorough, and transparent investigation of the hydrogeology at AP-3, which Georgia Power failed to do.

The 1977 and 1979 sinkholes obviously showed that this is a hydrogeologic environment where the processes leading to sinkhole collapse can operate I do not think application has shown that capping in place the CCRs have necessarily eliminated the karst-related risks at AP-3. Based on my concerns with lack of information in the current application, I will only make a few broad observations based on the data that have been presented.

7.2.1 Saturated Ash at the Bottom of AP-3

A cap over the ash footprint is designed to prevent vertical infiltration from above. However, as shown in Figures 1 and 2, sinkholes are not just induced from infiltration from above, but can form from the bottom up. As shown in the cross section below (Figure 10) the bottom part of the ash is saturated with groundwater. Each of the cross-section diagrams shows some material, either residuum or terrace material, between the ash and the limestone bedrock, which gives at least a visual sense of the materials acting as some kind of buffer, although there is no guarantee that the other unconsolidated material is itself is not subject to collapse into a sinkhole. The 1977 Law Engineering report (2010 Safety Assessment pdf p. 62) made it clear that this is not the case everywhere at A-3, apparently stating that the saturated ash was now sitting directly on top of the jointed (fractured) limestone bedrock:

> Further, the report state [sic] the removal of relatively impermeable material overlying the jointed bedrock had allowed water to move from the pond. Additionally, low to very high permeability measurements in materials below the dike, including solution cavities were encountered during coring operations.

Yet another characteristic of well-developed karst systems, because water can move so easily and quickly through them, is the that the position of the water table at the top of the saturated zone can fluctuate during storms more rapidly and with more vertical fluctuation than is typical for other hydrogeologic settings (Groves and Meiman 2004, 2005). There is at least some

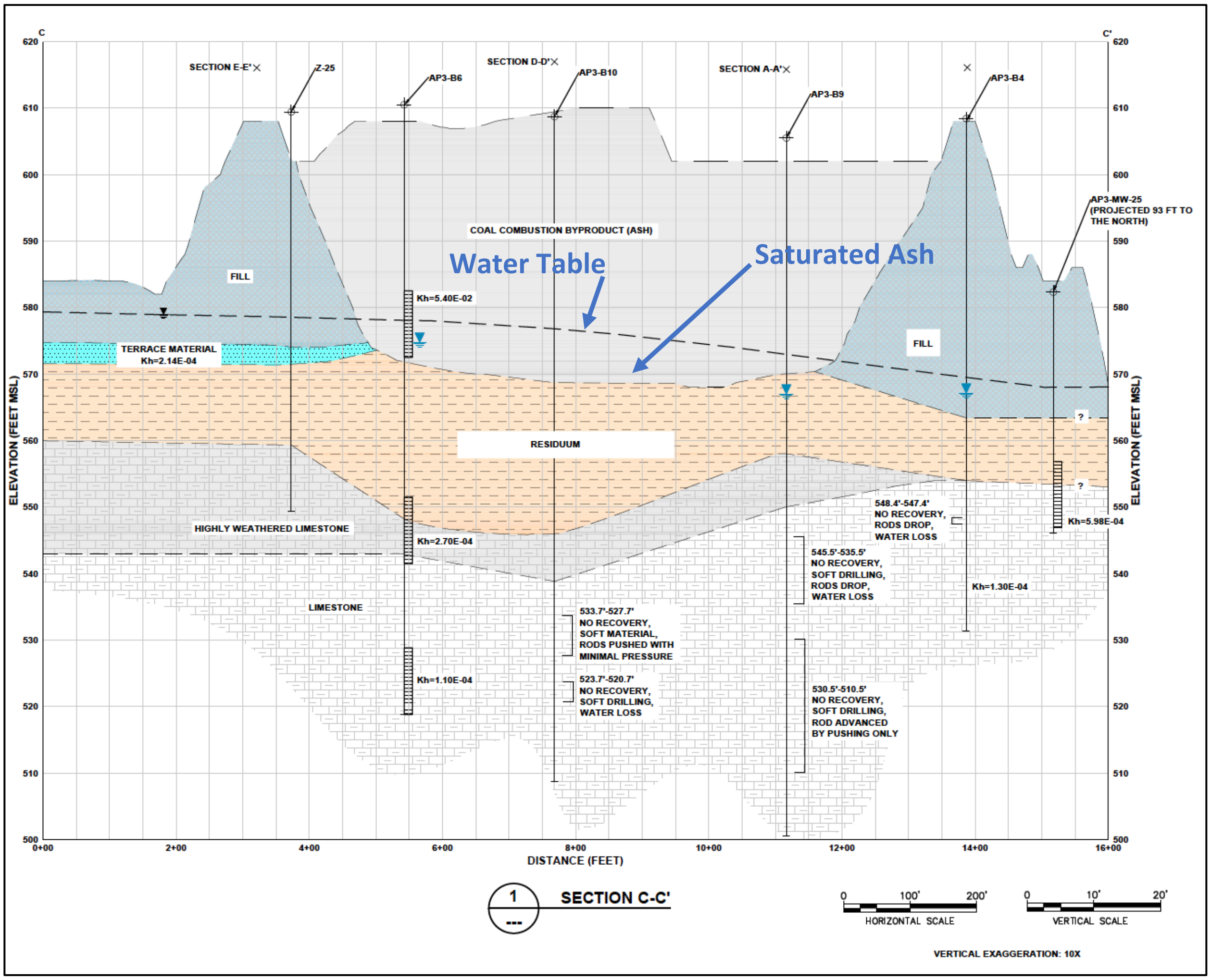


Figure 10. Cross section C-C' with area of saturated ash, and the top of the saturated zone, or water table, labeled.

possibility that water in the saturated ash moving vertically upwards and back down as storms pass through and the level of the Coosa River fluctuates could potentially drive CCR into the karst aquifer, with voids propagating upwards and loss of stability along the lines of the processes shown in Figures 1 and 2. In both cases the resulting sinkholes are initiated by loss of material from the bottom. Although water table data exist for the site, (Part B Application pdf p. 19) only a single day snapshot (June 4, 2018) has been provided and none with which to evaluate the rates or magnitudes of either storm or seasonal scale water table fluctuations.

7.2.2 Lateral Movement of Groundwater Beneath AP-3

Although the cap will presumably prevent the vertical infiltration of rainwater from above moving downward, groundwater moves laterally beneath the site (Figure 11). While it would seem that a basic element to evaluate the stability of AP-3 would be a quantitative evaluation of the hydrology of vertical and lateral water flows beneath the site under storm and seasonal scale variation, other than a map of groundwater flow for a single, selected day, Georgia Power failed to provide this type of data in its application.

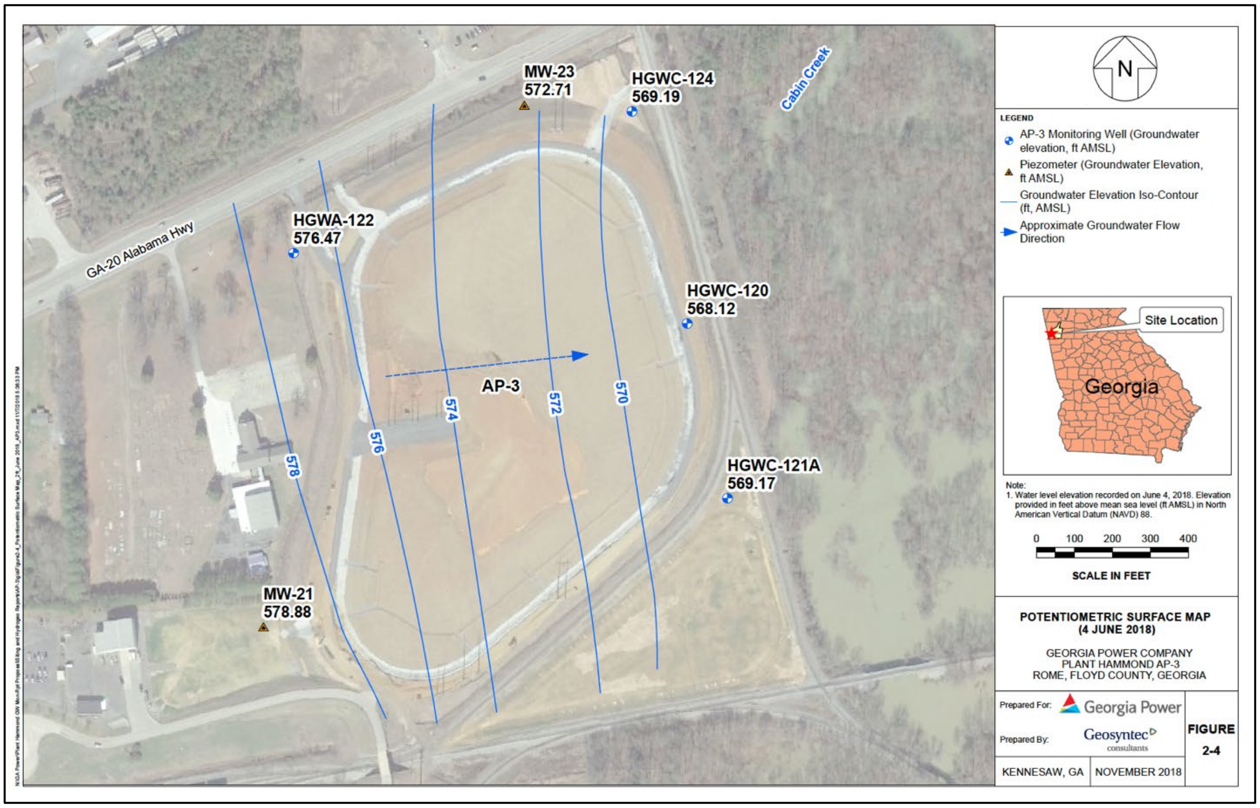


Figure 11. Map showing eastward lateral groundwater flow beneath AP-3.

Some lateral groundwater flow velocities were provided, but not only are they potentially subject to the same analytical problems described in the discussions above, any discussion of flow velocities in the limestone bedrock is missing entirely.

8. Concluding Statement

As I have detailed throughout this report, in my opinion, while the available raw data themselves for the various investigations appear to be sound, there are numerous problems with omissions, incorrect analysis, and misinterpretation of those data, which have led Georgia Power to minimize concerns about karst and the associated risks.

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