

## **The hole story: How a sinkhole in a phosphogypsum pile was explored and remediated**

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### **ABSTRACT**

On June 27, 1994, an erosion sinkhole occurred in the original 200-foot high phosphogypsum stack at the New Wales Plant of IMC-Agrico Company. As a result, a plan of action was expediently developed to assess groundwater impacts and ensure that any contamination is contained on property, recovered, and appropriately handled at the plant. Shortly thereafter, resources were mobilized to define the extent of the erosion cavity in the natural confining unit beneath the stack, and to formulate and undertake appropriate repairs.

Contamination was effectively contained on property by using the plant production wells as recovery wells. Measures were implemented to allow the plant to continue to efficiently consume the recovered water. Hence, in spite of the sinkhole, there has been no impact on groundwater resources beyond the plant site.

The geologic anomaly in the confining unit was remediated by injecting more than 3,800 cubic yards of pea gravel concrete some 400 feet beneath the surface of the gypsum stack. This remedial action activity was accomplished via implementation of an extensive coring and grouting program, using angle drilling and as many as 50 grout injection casings.

Water levels in piezometers tapping various formations adjacent to the sinkhole have recovered, confirming that the throat of the erosion cavity has been successfully plugged and that the confining unit has been restored. Moreover, contaminant indicators in the plant production wells have exhibited a systematic long term downward trend consistent with the successful resolution of this natural sinkhole phenomenon.

### **BACKGROUND**

Florida is internationally recognized as one of the most popular tourist destinations in the world. Every year, tens of millions of visitors come to the Sunshine State for its white sand beaches, theme attractions and natural beauty. Florida also hosts the citrus industry, and another industry which contributes to the state's growing economy and which is an essential part of a network that feeds the world population. This baseline industry deals with the mining and processing of phosphate into fertilizer, as well as into animal feed and other crop nutrient products. Millions of tons of the mineral are mined annually from the phosphate rich soils of Central Florida, and are subsequently refined into concentrated phosphate which is shipped for use in agriculture to promote plant growth and improve crop yields. A by-product of the refining process is gypsum (or phosphogypsum), a white substance which is stored in large piles or stacks. The stacks, which take years to create, reach heights up to 200 feet and cover several hundred acres. By-product phosphogypsum is generally transported as a slurry to the disposal area where the silt-sized gypsum particles are allowed to settle. The transport water is decanted and recirculated to the concentrated phosphate plant for re-use. The stack is gradually and systematically raised using the upstream method of construction. In this method, gypsum is excavated from within the perimeter of the disposal area and periodically cast onto previously sedimented gypsum to raise the perimeter dike and provide additional storage capacity. The top surface of the stack is generally maintained ponded to promote evaporation. Water stored atop the stack and entrained within the pores of the sedimented gypsum is acidic (pH on the order of 1.5 to 2.0) and contains elevated concentrations of inorganic constituents such as fluoride, phosphate, sodium and sulfate.

One of the largest suppliers of concentrated phosphate in the world is IMC-Agrico Company, and its largest plant is located in Polk County, Florida, about 70 miles southwest of Orlando. The company's New Wales Plant produces 3.5 million tons of fertilizer products annually, principally diammonium phosphate. The plant also generates approximately 23,000 tons of by-product gypsum every day. The complex includes an original phosphogypsum stack which was approaching capacity in 1994, and a new lined state-of-the-art disposal area which is currently used for phosphogypsum storage. The old stack is surrounded by a pond and channels used to cool and recirculate process water for re-use at the plant.

On Monday, June 27, 1994, workers from the plant were making a routine inspection on top of the original stack when they encountered an unusual feature that had not been there before. A huge hole had opened in the top of the stack. An overhead view from a helicopter and subsequent measurements revealed that the circular hole was 160 feet across at the top. It tapered to a 110-foot wide shaft that extended vertically downward to the base of the 200-foot high phosphogypsum stacking facility. After examining the feature, the company's engineers, along with its consultant, Ardaman & Associates, Inc., determined that the stack had fallen victim to an erosion sinkhole. In fact, the 200-foot deep shaft was connected to an erosion cavity which was infilled with collapsed gypsum blocks, and which extended over 400 feet into the natural soil and rock formations beneath the phosphogypsum stack (see Figure 1).

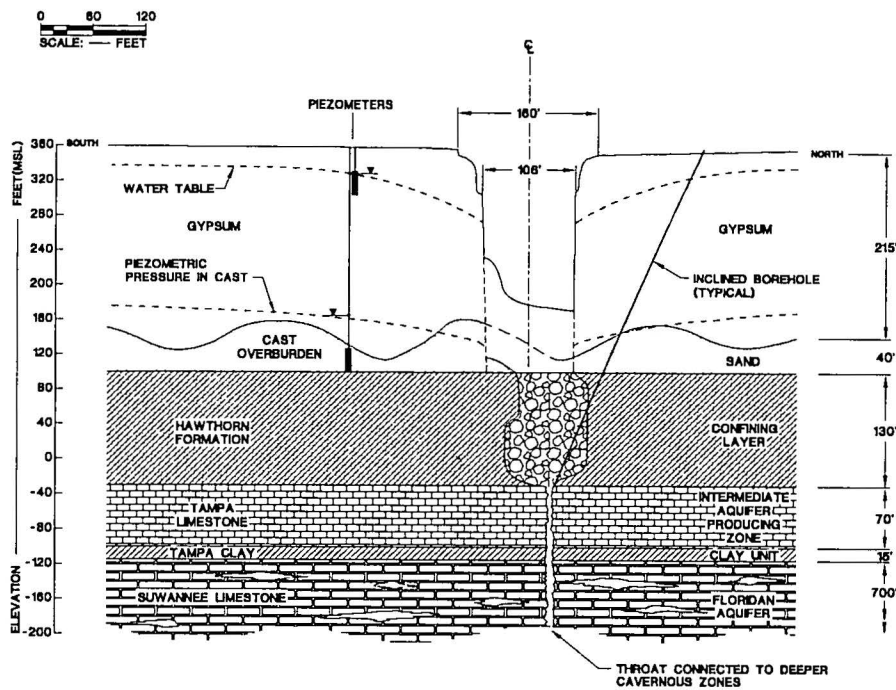


Figure 1. Geologic Cross Section Depicting the Sinkhole

Sinkholes are not an uncommon phenomenon in Florida. In addition to hosting sunny beaches, theme attractions and an industrial community, the state also hosts a karst geology. During the glacial ages, over a hundred million years ago, the deeper limestone formations were exposed to the atmosphere and subjected to weathering. Because of the solubility of carbonate rock in rain water, solution cavities developed along joints and bedding planes within the exposed rock formations. The cavernous limestone was then buried beneath more recent sedimentary deposits. Clays and then sand were deposited over the limestone formations. The clays (including mudstones and dolomitic limestones) formed a confining layer, i.e., a natural liner, separating the surficial sandy aquifer from deeper limestone aquifers. The type of sinkhole that Florida is famous for is caused by the progressive erosion or piping of unconsolidated sandy soils into an underground cavity. For such a sinkhole to develop, a geologic anomaly (joint or vertical solution channel) filled with erodible material must be present in the natural confining unit, and a downward hydraulic gradient must exist between the surficial sands and underlying artesian aquifers. Under these conditions, the erosion process progresses upward in the confining unit while the sand is gradually transported downward into the pre-existing cavernous system within the limestone formations. As this occurs, a large void or erosion cavity is formed within the surficial deposits. Eventually, the cavity increases in size to the point where its roof is no longer stable. A sudden collapse of the cover then occurs, creating a depression referred to as a sinkhole. Although sinkholes are not an uncommon natural phenomenon in Central Florida, the sinkhole which occurred in the original stack at the New Wales Plant was one of the largest of its kind; and because it was located in a disposal area used to store a by-product from a concentrated phosphate plant, it presented major structural design as well as unique environmental challenges.

#### CONTAINMENT OF GROUNDWATER PLUME

Upon determining that the phosphogypsum stack had fallen victim to a sinkhole, the stack was immediately deactivated, and the gypsum slurry was routed exclusively to the new lined phosphogypsum disposal facility. The occurrence of a sinkhole meant that the 130-foot thick confining layer beneath the stack had been breached causing contaminated ponded water and seepage water from the stack to flow into an underlying artesian aquifer, the Floridan Aquifer, which is the major water supply source in Central Florida. The immediate concern was to assess how the sinkhole had impacted the groundwater and to make sure that any contamination would be contained on property.

The gypsum stack was located upgradient from the plant site which included two deep groundwater withdrawal wells. The engineering team responded rapidly to alleviate environmental concerns and determined that any groundwater impacts could be effectively contained on site within the zone of influence of the plant production wells. The zone of capture for these wells was quickly documented by actual measurements of water levels in over 20 monitor wells (see Figure 2). The team was able to confirm that as long as the plant wells were pumped at normal withdrawal rates (on the order of 8 million gallons per day) to meet the plant's operating needs, contaminated groundwater would be contained and captured on site. In fact, the production wells, acting as recovery wells, prevented any contaminants from migrating off property by recycling the water back into plant production. Water quality data in two deep Floridan Aquifer monitor wells located downgradient from the plant continue to document, as expected, the absence of groundwater quality impacts beyond the plant site.

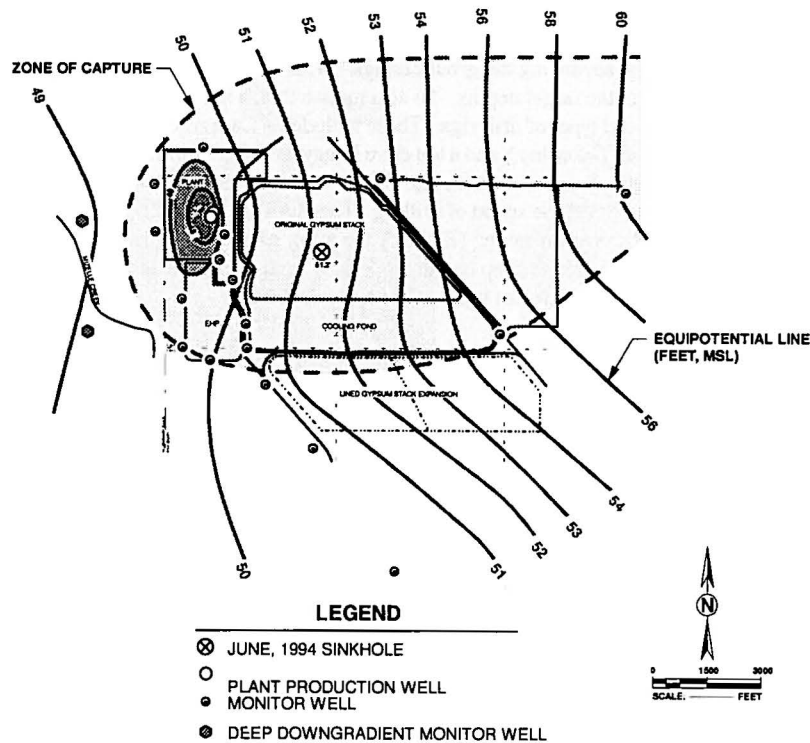


Figure 2. Zone of Capture of Production Wells (As Documented on June 28, 1994 in Floridan Aquifer Monitor Wells)

Shortly after detecting impacts in the plant production wells, IMC-Agrico Company implemented measures to allow the New Wales Plant to continue to withdraw and efficiently consume the impacted groundwater. As a result, in spite of the sinkhole, there has been no impact whatsoever on water resources beyond the plant site.

#### EXPLORING THE SINKHOLE

With the immediate environmental concerns averted, the company proceeded to repair the sinkhole beneath the stack. Resources were mobilized to define the extent of the erosion cavity within the 130-foot thick natural confining layer beneath the stack, and to formulate and then implement appropriate remedial actions. A subsurface exploration program was conducted in July and August, 1994. Six exploratory boreholes were drilled around the sinkhole. So that the drill crews could operate a safe distance from the hole, four of the coreholes were drilled on an incline to lengths up to 430 feet. Gyroscopic and single-shot directional surveys were conducted in the drill casings to pinpoint their actual locations in space. A cross hole seismic survey was then conducted in the exploratory boreholes.

The seismic survey consisted of performing a series of shots by sequentially igniting explosive charges at 5-foot centers in one of the casings, used as a shot hole. As soon as the 26-gram seismic charge was ignited, it triggered the collection of data in a receiver hole where a 115-foot long string of 24 geophones was located. The arrival time of the compression wave at each geophone was used to calculate the seismic velocity. After performing measurements sequentially in all coreholes and obtaining seismic velocities from multiple locations using a total of over 200 seismic blasts, an attempt was made to develop a tomographic image of the erosion cavity. Although the velocity contrasts were not large enough to allow for accurate resolution of a "cat-scan" image, the field exploration program verified the presence of a large cavity in the confining unit and provided an opportunity to estimate its size and configuration. The cavity was infilled with cemented gypsum "blocks" or "boulders" that had previously collapsed from the gypsum stack. Based upon results from the field exploration program, a plan of action for repairing the sinkhole was developed. The objective of the plan was to "plug" the throat of the erosion cavity and to restore the confining unit beneath the stack to prevent further loss of material, and to inhibit continued leakage of seepage water into the Floridan Aquifer.

## REPAIRING THE DAMAGE

The problem was remediated and the natural confining unit restored by injecting more than 3,800 cubic yards of pea gravel concrete and liquid grout into the erosion cavity in the confining unit. The remediation plan required injecting grout materials at high pressure some 400 feet beneath the surface of the gypsum stack, using as many as 50 grout injection casings. The repair plan had to be flexible enough to allow for changes in drilling/grouting procedures and grout mixes as needed to accommodate uncertain and variable conditions underground. An extensive contractor prequalification and negotiation process was conducted by IMC-Agrico Company and Ardaman & Associates, Inc. in order to select the main drilling/grouting contractor. The contractor needed to demonstrate competence in drilling deep angle holes, site batching of a large variety of mix designs, flexible and efficient grout transport, injection of grout at high pressure, and efficient extraction of 450-foot long grout casings. Hayward Baker Inc. was selected for this assignment.

Because the cavity was located beneath the center of an open shaft, and since drill rigs could only approach to a safe distance from the edge of the hole, angle drilling was adopted for advancing the grout casings. With this approach, it was critical to be able to set the injection casings at the proper angle to "hit" the cavity at the target depths. To accomplish this, a multi-step angle drilling approach was implemented utilizing three telescoping casing sizes and several types of drill rigs. These included a Casagrande C-8 drill rig geared for "blow and go" type angle production drilling (mobilized by Hayward Baker Inc.), and a top drive Longyear BB20 wireline coring rig (mobilized by Boart Longyear Company). The C-8 drill rig was outfitted with a carousel which allowed 104 feet of drilling tools to be stored in 13-foot sections and to be added to the drill string mechanically which increased the speed of drilling. The BB20 angle drill rig was used to obtain 4-inch diameter core samples in order to: (i) define the limits of the erosion cavity; (ii) verify the grout spread from prior injections; and (iii) prepare a pilot hole for setting the grout pipe. The New Wales Plant machine shop had to work daily (and occasionally nightly) making adapters to accommodate incompatible english and metric tools used by the different types of specialty drill rigs.

The drilling methodology consisted of first installing a 9-inch diameter starter casing to a depth of 20 to 40 feet using the C-8 drill rig. The starter casings were set at various angles to initiate the hole on a line that would ultimately enter the cavity at a predetermined elevation. Using the C-8 drill rig, a smaller diameter 6.75-inch surface casing was then installed through the starter casing and advanced about 300 feet until it was seated into the top of the confining unit. Using the BB20 drill rig, a corehole was then advanced through the surface casing, into the erosion cavity to the target depth. A 4.5-inch diameter grout casing was then set in this corehole in 13-foot sections by the C-8 drill rig (and occasionally by the BB20 rig). It was very important that the grout be injected from a known point, so a Fotobore directional survey was performed inside the 400 to 450-foot long grout casings to determine their inclination and bearing, i.e., their exact location in space. Any deviation from the target inclination and bearing of a casing had to be accounted for in planning future grout holes as needed to achieve complete grout coverage at all levels within the confining unit. Moreover, the location accuracy of angle drilling at depth had to be continuously updated and refined to make the necessary adjustments needed to "hit the mark".

Because of the corrosive nature of the pore water, the steel casings had a very limited life span. The operations had to be planned, therefore, to complete drilling and grouting as expeditiously as possible after installation of a surface casing at any given location. Round-the-clock operations were carefully planned to expedite the repair work and to allow for efficient coordination of simultaneous drilling and grouting activities in the very limited work area available around the scarp, while, at the same time, precluding grout from flowing from an injection casing towards another corehole that was still being advanced or that had not as yet been grouted. This task was particularly challenging because of the close proximity of a large number of inclined grout casings.

Over 100 grout mixes were tested to select special mixes that were pumpable, would not segregate or bleed, were compatible with acidic pond water, and would exhibit the desired strength and hydraulic conductivity over a wide range of slumps. Aggregates used in the concrete mix were obtained from nearby local sources, i.e., a mine (sand tailings) and beneficiation plant (pea gravel) operated by IMC-Agrico Company. The primary pea gravel concrete grout mix selected contained aggregates, fly-ash, Type II cement, bentonite, water, and a plasticizer used to maintain strength at high slumps. The secondary liquid grout was formulated with fly-ash, Type II cement, bentonite, and a plasticizer as needed. Both mixes were relatively rich in cement.

An on-site concrete batch plant, a high capacity slurry batch plant, three ready-mix trucks and a Schwing 5000 piston-displacement pump were mobilized to expedite implementation of any changes in grouting guidelines in response to on the spot decision making authority and to provide the desired flexibility, e.g., the potential for changing the grout mix formulation even just prior to injecting the grout. The cavity was filled using an "upstage" grouting sequence wherein each grout casing was slowly extracted while grouting operations were in progress. A 2300 Vulcan vibratory hammer attached to specially designed inclined leads of a 150-ton crane was used to assist in the casing extraction process so as to minimize the potential for the inclined casing getting struck during the high pressure grout injection. (Casings that got stuck and could not be retracted were perforated in-place using hydro-blasting equipment, and were then abandoned by injecting liquid cement grout under pressure.)

Each injection casing was sequentially used to grout the erosion cavity from bottom to top (see Figure 3). The casing was slowly extracted in increments, while grout injection operations were underway. The grout injection operation typically consisted of pumping grout, produced at the batch plant on-site, into concrete trucks, which delivered the mix to a piston-placement Schwing 5000 pump (rated at 2000 psi) that directed the grout at high pressure into the grout casing. When it was no longer possible to inject grout into a casing, the grouting operation proceeded to the next casing, and so on. Installation of the casings for grout injection purposes was phased, progressing from the

perimeter towards the center of the erosion cavity and from deeper target levels to shallower levels in the confining unit (see Figure 4). The objective was to seal the throat or bottom of the cavity in the confining unit prior to grouting the bulk of the erosion cavity in order to minimize grout losses into the underlying cavernous network. Holes targeting relatively shallow levels in the erosion cavity were generally extended to greater depths in order to sample previously injected grout, and in order to provide some redundancy, i.e., an opportunity for injecting additional primary grout (pea gravel concrete) or secondary grout (liquid grout), if feasible, even where adequate grout coverage had been previously achieved.

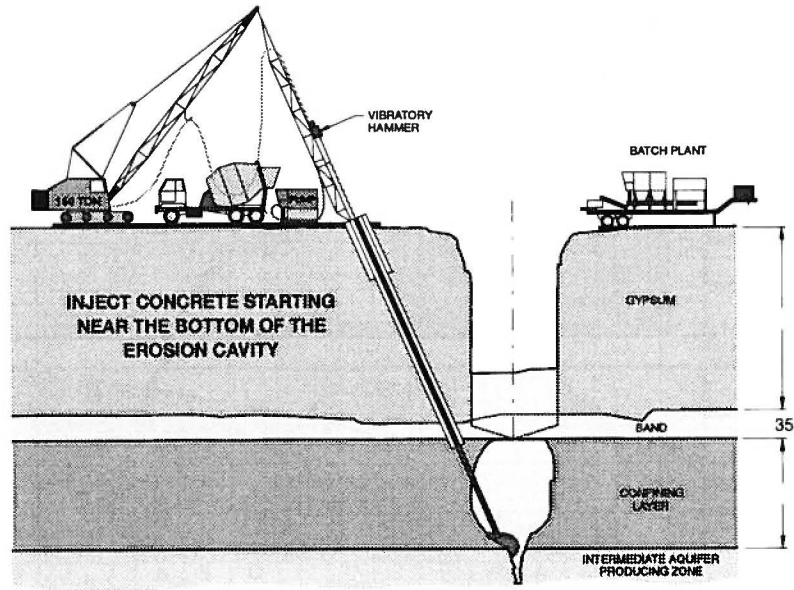


Figure 3. Injecting Concrete Starting from the Bottom of the Erosion Cavity

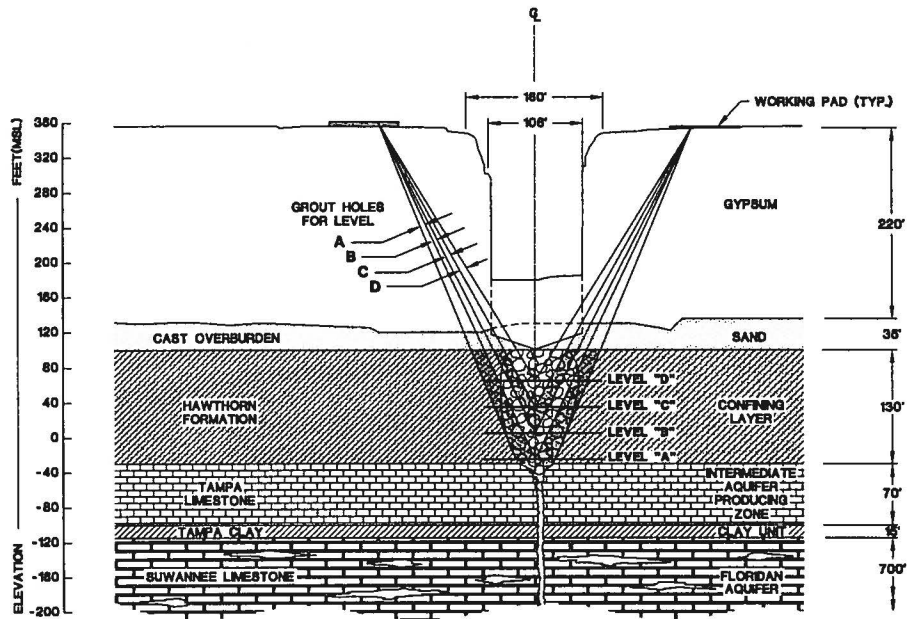


Figure 4. Cross Section Illustrating Target Grout Levels.

Based on a total of 55 coreholes that penetrated the erosion cavity in the confining unit, the cavity occupied a total volume on the order of 19,200 cubic yards (cyd). Based on the cores recovered, the cavity was primarily infilled with cemented gypsum "blocks" or "boulders" (generally ranging in thickness from about 2 to 8 feet) that had previously collapsed from the gypsum stack. The concrete was injected into the erosion cavity at high pressure not only to fill the voids but also to cause the grout to flow via hydraulic fracturing. In fact, the grout was found to be intimately bonded to the gypsum blocks within the erosion cavity. A grout spread distance in excess of 15 feet (and up to 25 feet) was documented from core samples retrieved from the erosion cavity.

The grout take per hole exhibited a marked decrease from an average of 200 to 350 cyd/hole (between December 1994 and February 1995), to less than 50 cyd/hole (beginning in February 1995) when the throat of the sinkhole was plugged (see Figure 5). From then on, the grout take remained relatively low, i.e., generally on the order of 25 cyd/hole or less (from February 1995 through April 1995), indicating that the erosion cavity had become tightly filled and that the grout was primarily spreading during these latter stages via the mechanism of "hydraulic fracturing". Even though the grout take remained low, a conscious decision was made to proceed with implementation of the plan of action through completion in order to restore the confining unit to the greatest extent possible.

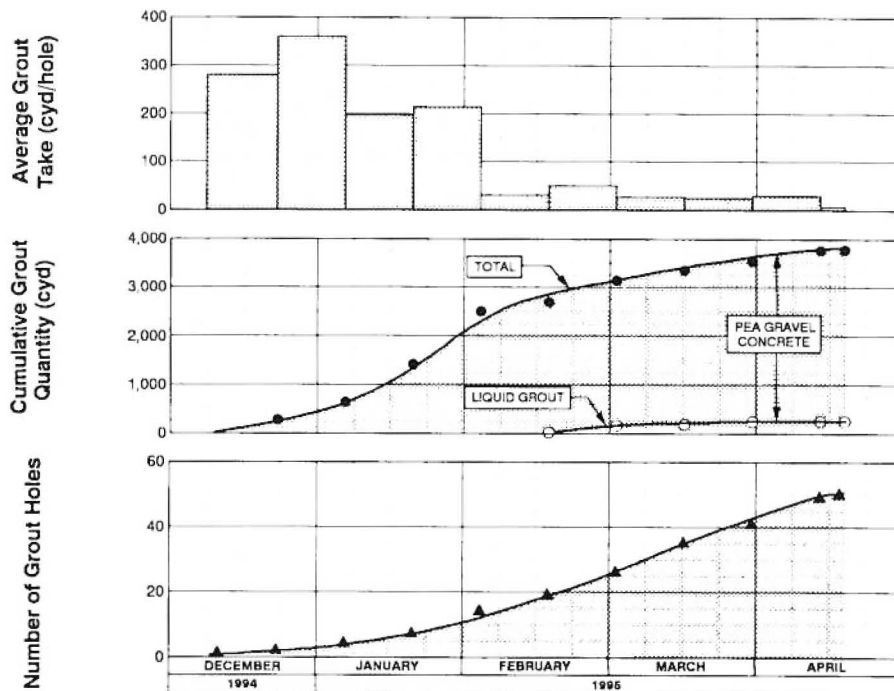


Figure 5. Chronologic Overview of Grouting Activities

The total grout quantity injected consisted of 3,522 cyd of 7-inch to 11-inch slump pea gravel concrete, and 261 cyd of secondary liquid (slurry) grout generally batched at an average Marsh Funnel viscosity on the order of 70 seconds. (Approximately 131 cyd of additional grout were also used during abandonment of stuck casings.) The strength of samples of grout retrieved from the erosion cavity ranged from about 1,500 psi to as much as 8,000 psi, which was significantly greater than the target range of 500 to 1,000 psi. The coefficient of permeability of cored samples of grout ranged from a low of  $7 \times 10^{-9}$  cm/sec to a high of  $2 \times 10^{-7}$  cm/sec, in compliance with the specified range of  $10^{-6}$  to  $10^{-7}$  cm/sec.

#### ASSESSING THE EFFECTIVENESS OF THE REPAIRS

Extensive monitoring of the water table and piezometric levels in the confining unit was undertaken in order to determine the progress and effectiveness of the remedial work aimed at plugging the erosion cavity. Water levels in piezometers tapping the cast overburden sands (beneath sedimented gypsum) and underlying confining unit, in the vicinity of the sinkhole, have exhibited a significant rise (on the order of 90 feet) and have sustained high levels since March 1995, confirming that the throat of the erosion cavity has been successfully plugged. In fact, recently measured piezometric water levels in the vicinity of the sinkhole are consistent with what one would expect in areas of the phosphogypsum stack that have not been affected by the sinkhole. Moreover, the water level in the hole within the stack rose by more than 140 feet, to within a depth of 20 feet from the sedimented gypsum surface, and has been very stable since the completion of the sinkhole remediation efforts, indicating that downward leakage has essentially ceased. The water table which had been depressed has also recovered.

Shortly after occurrence of the sinkhole in late June 1994, chemical concentrations in the plant production wells increased, reaching a "peak" plateau in December 1994. In spite of the impacts attributed to the sinkhole, the water quality in the plant production wells has

remained in compliance with primary drinking water standards at all times. Moreover, contaminant indicators in the plant production wells have confirmed the successful plugging of the erosion cavity. Beginning in mid-March 1995, orthophosphate concentrations began reflecting a systematic long-term downward trend (see Figure 6). Other indicator parameters (i.e., sodium, sulfate and total dissolved solids) also began to exhibit a long-term downward trend due to curtailment of the seepage attributed to the sinkhole. Even though the sinkhole was successfully remediated, and the hydraulic connection between the phosphogypsum stack and the Floridan Aquifer was plugged, it may take some time for the water quality in the production wells to return all the way to background concentrations. As noted above, most contaminant levels in the production wells have decreased systematically since March 1995. Nevertheless, it is anticipated that several additional years may be required for the production wells to remove all contaminants from the aquifer.

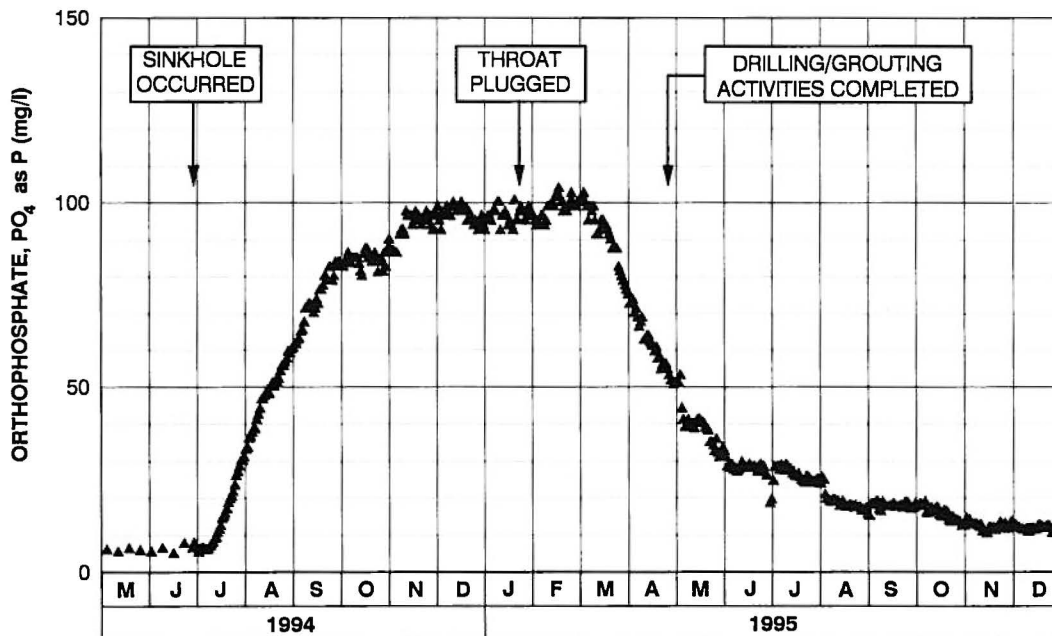


Figure 6. Water Quality in Production Well

#### CONCLUSION

Through the combined efforts of a committed owner, concerned regulators, a creative engineering team, and a responsive contractor, a naturally occurring sinkhole phenomenon was managed to the benefit of all parties, the community, and the environment. The team responded rapidly to assess, evaluate, and successfully remediate the sinkhole in the 200-foot high phosphogypsum storage area, using construction methods and procedures adapted specifically to this unique application. Remediation activities were successfully completed on schedule, in April 1995, at a cost of 6.8 million dollars. Groundwater and potentiometric levels have recovered and returned to pre-sinkhole levels. Contaminant concentrations in the plant production wells are on their way to background levels, and all groundwater impacts have been contained entirely on plant property. The repair work was completed to the satisfaction of the state regulators and the Technical Advisory Committee that they formed to assist them in their evaluations. The cooperation between owner, engineer, contractors and regulators was quite effective.

After remediating the erosion cavity and restoring the natural confining unit, the hole in the stack was re-filled with sedimented gypsum. Controlled filling of the hole with gypsum slurry was initiated in late June 1995 and progressive filling is still ongoing to restore the stack's macro-permeability in preparation for closure.

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