Sinkhole Remediation at a Phosphogypsum Stack

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Background

On June 27, 1994, an erosion sinkhole occurred in the 200-foot high original phosphogypsum storage area at the New Wales Plant of IMC-Agrico Company, in Polk County, Florida. The hole measured 160 feet in diameter at the surface. It tapered down to a 110-foot wide shaft which stood essentially vertical from the top to the base of the 200-foot thick sedimentary gypsum deposit (see Figure 1). The open shaft was connected to an erosion cavity which was infilled with collapsed gypsum blocks and which extended into the natural soil and rock formations beneath the phosphogypsum stack to a depth of 400 feet.

Erosion sinkholes are not an uncommon phenomenon in Florida, a state which hosts a karst geology. For an erosion 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 eroded material is gradually transported downward into a pre-existing cavernous system within the artesian aquifers (formed during the glacial ages, millions of years ago, when the deeper carbonate rock and limestone formations had been exposed to weathering). As the sand gradually erodes downward, a large cavity is formed within the surficial deposits. When the erosion cavity increases in size to the point where its roof is no longer stable, a sudden sinkhole collapse occurs. Although sinkholes are not an uncommon natural phenomenon, the sinkhole which occurred in the stack at the New Wales Plant was one of the largest of its kind;

and because the subject sinkhole was located in a disposal area used to store a by-product from a concentrated phosphate chemical plant, it presented major structural design as well as unique environmental challenges.

Upon determining that the original phosphogypsum stack had fallen victim to a sinkhole, the old stack was immediately deactivated, and the gypsum slurry was routed exclusively to a new lined phosphogypsum stacking facility. Moreover, a plan of action was expediently developed to assess impacts on groundwater resources and to ensure that any contamination was contained on property. Shortly thereafter, resources were mobilized to define the extent of the erosion cavity in the 130-foot thick natural confining unit beneath the stack, and to formulate and undertake appropriate repairs.

Containment of Groundwater Plume

The sinkhole caused 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 the State of Florida. The Owner & Engineer 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 corresponding zone of capture (Figure 2) was expediently documented, and was rechecked on several occasions (by actual measurements of water level gradients in over 20 monitor wells), in order to provide reasonable assurance that the contaminant plume would continue to be effectively contained on property. The Owner & Engineer were able to confirm that as long as the plant wells (designated SF-1 and NF-1) were pumped at a combined production rate of 5000 to 6000 gallons per minute to meet the plant's normal 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. Water quality data in two deep downgradient Floridan Aquifer monitor wells continue to document, as expected, the absence of groundwater quality impacts beyond the plant site. (Note that the sinkhole did not impact the intermediate aquifer system at the site.)

Shortly after detecting impacts in the plant production wells, and while the contaminant breakthrough curve was still in progress, projected peak chemical concentrations in the recovered groundwater were reliably predicted using the computer program RANDOMWALK as well as calibrated values of aquifer dispersivity, fracture porosity and flow velocity backfigured from the documented travel time of the contaminant plume to the production wells. These predictions provided IMC-Agrico Company with the opportunity to implement measures in a timely manner to allow the New Wales Plant to continue to withdraw and consume the impacted water. These measures included: (i) increasing the sulfuric acid plants' cooling tower blowdown to avoid fouling heat exchangers; (ii) optimizing the reverse osmosis system to accommodate higher impurity levels in the feed water; (iii) optimizing the operation of the demineralizer system; and (iv) utilizing partially contaminated water in lieu of well water in non-critical applications. As a result, in spite of the sinkhole, there has been no impact on groundwater resources beyond the plant site, as well as no impact on surface water resources, i.e., no discharges of impacted water.

Formulating a Repair Methodology

A subsurface exploration program was conducted in July and August 1994. The field exploration program overcame difficulties related to providing safe access to the erosion cavity by employing angle drilling from the edge of the vertical scarp. Gyroscopic and single-shot directional surveys were conducted in the drill casings to pinpoint the actual locations of six exploratory coreholes which had been advanced to inclined lengths up to 430 feet. A cross hole seismic survey was then conducted in the exploratory holes to assist in defining the location, extent, and nature of the erosion cavity in the confining unit beneath the stack. A plan of action for sinkhole repair was then formulated. Its objective was to restore the structural and hydraulic integrity of the 130-foot thick confining unit separating the surficial aquifer from deeper artesian aquifers.

From the outset, it was evident that restoration of the confining unit could best be accomplished with cementatious grout placed by pressure pumping through grout pipes drilled at an angle into the erosion cavity, as needed to provide safe working conditions for the construction crews. A team of experts was consulted to assist in formulating details of the remedial approach. The group included specialty contractors from throughout North America. It was deemed of paramount importance that the repair plan be flexible to allow for changes in drilling/grouting procedures and grout mixes in order to accommodate uncertain and variable conditions underground.

A multi-step drilling methodology needed to be implemented while advancing each grout casing to inclined lengths of up to 450 feet (see Figure 3). Three telescoping casing sizes needed to be used in advancing each hole. Because of the corrosive nature of the pore water (pH on the order of 1.5 to 2.0), the 300-foot long steel surface casings (also used as inclined guides to the grout 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. Moreover, several types of rigs had to be used. They included a Casagrande C-8 rig geared for "blow and go" type production drilling; and a top drive BB20 wire line rig, developed by Longyear (and mobilized for the first time ever on this project), used to obtain large 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 type of specialty drill rigs.

Precise angle drilling was required to assure that the grout casings were terminated within the cavity and at the prescribed elevations. Detailed surveys and measurements needed to be taken to start the casing installation according to predetermined angles. A directional survey was to be performed inside each casing to determine precise bearing and inclination. The planned injection points had to be constantly evaluated and field modified. Information had to be collected and processed on a real time basis, generally overnight, in order to optimize grout placement. 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. 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".

An on-site concrete batch plant and three ready-mix trucks were mobilized to allow for expediting 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 via a high pressure piston-displacement pump (Figure 3). An upstage grouting sequence was adopted wherein each grout casing was slowly extracted while grouting operations were in progress. A vibratory hammer attached to the 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 in grout. (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.)

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.

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 hole that was still being advanced or that had not been grouted yet. This task was particularly challenging because of the close proximity of a large number of inclined grout casings (Figure 4).

Implementation of Remedial Activities

The geologic anomaly in the confining unit was remediated and the natural confining unit restored by injecting more than 3,800 cubic yards of pea gravel concrete (as well as liquid grout) some 400 feet beneath the surface of the gypsum stack, using as many as 50 grout injection casings advanced via angle drilling. After seating a 6.75-inch diameter, 300-foot long, surface casing into the top of the confining unit, a corehole was advanced into the erosion cavity to the target depth, in preparation for setting a 4.5-inch diameter grout casing in the hole (see Figure 3). A Fotobore directional survey was performed inside the 400 to 450-foot long grout casing to determine its exact location. The upstage grouting sequence was then implemented wherein each casing was sequentially used to grout the erosion cavity from bottom to top. 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 pump 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 (Figure 5). 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 (i.e., pea gravel concrete) or secondary grout (i.e., liquid grout), if feasible, even where adequate grout coverage had been previously achieved.

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), as illustrated in Figure 6. 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, thus forming a "new material" designated "gypcrete" (see Figure 7). A grout spread distance in excess of 15 feet (and up to 25 feet) was documented from core samples retrieved from the erosion cavity.

As illustrated in Figure 8, 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. 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.

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 generally ranged from about 1,500 psi to as much as 8,000 psi, i.e., the strength 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 7×10^{-9} cm/sec to a high of 2×10^{-7} cm/sec, in compliance with the specified range of 10^{-6} to 10^{-7} cm/sec.

Assessing the Success of the Repairs

Water Level Trends

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 the 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 (see Figure 9). 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 geologic anomaly. 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. Evaluation of piezometric water level data indicates that the cast overburden beneath the gypsum is no longer recharging the sinkhole. Rather, after plugging the throat of the cavity and restoring the confining unit, the water in the hole within sedimented gypsum started recharging the cast material, i.e., seepage in the cast overburden started radiating away from the hole towards the existing perimeter cooling pond system which surrounds the stack, and which acts as a local relief for lateral seepage from the stack.

Water Quality Trends

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 (Figure 10). Other indicator parameters (i.e., sodium, sulfate and total dissolved solids) also began to exhibit a similar 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 years may be required to completely remove all contaminants from the aquifer because purging an aquifer from contaminants generally occurs at a much slower rate than that characterizing the breakthrough front, as schematically illustrated, for example, by the theoretical concentration in a continuous stirred tank reactor presented in Figure 11. Moreover, purging of the aquifer from impacts is delayed by the redissolution of some of the reacted precipitates in the impacted area, as well as the dissolution of as much as 26,000 cyd of gypsum crystals that have fallen from the stack into the aquifer system, as schematically illustrated by the flow pattern in Figure 12. Laboratory test results indicate that whereas one mixing cycle is sufficient to contaminate a limestone sample, more than 8 rinsing cycles are in fact required to clean it. Note that as much as 5 years may be required to dissolve all the gypsum that has fallen into the aquifer assuming that dissolution occurs at a rate controlled by the solubility of gypsum in fresh water.

Epilogue

Through the combined efforts of a committed owner, concerned regulators, and a creative engineering team, 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 level of 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 and original appearance.

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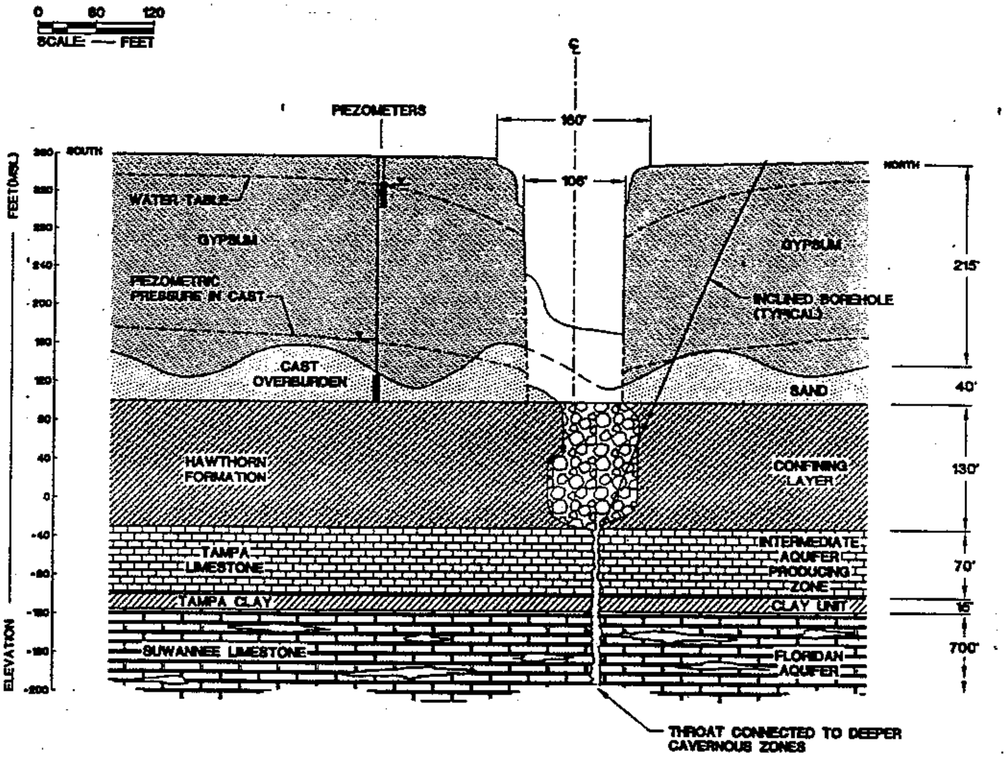


Figure 1. Geologic Cross Section Depicting the Sinkhole

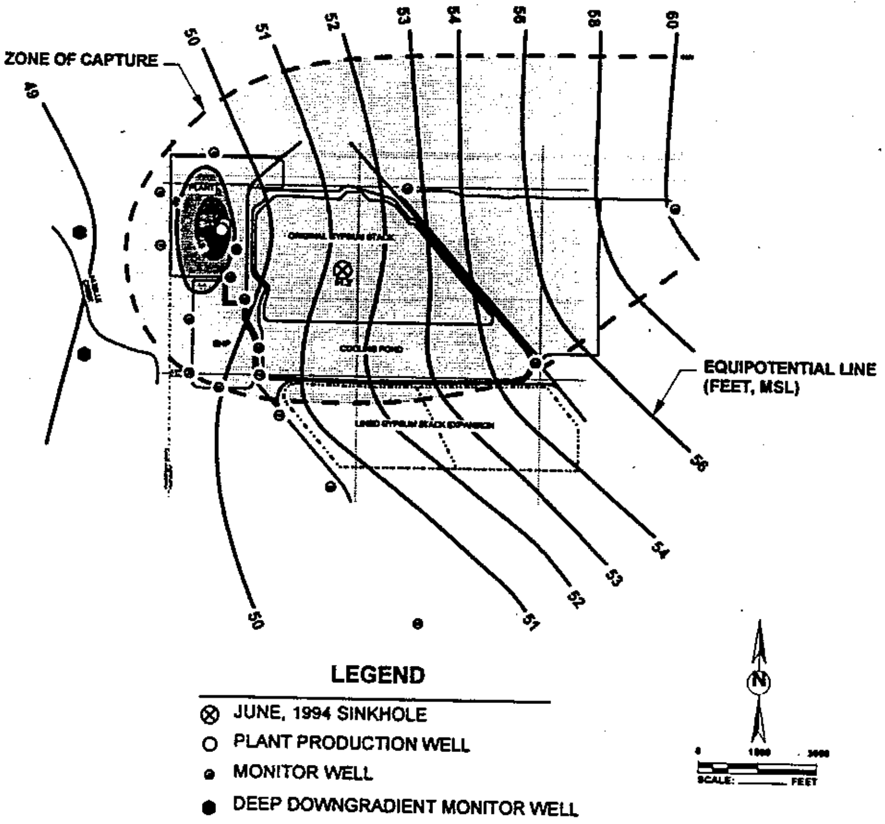
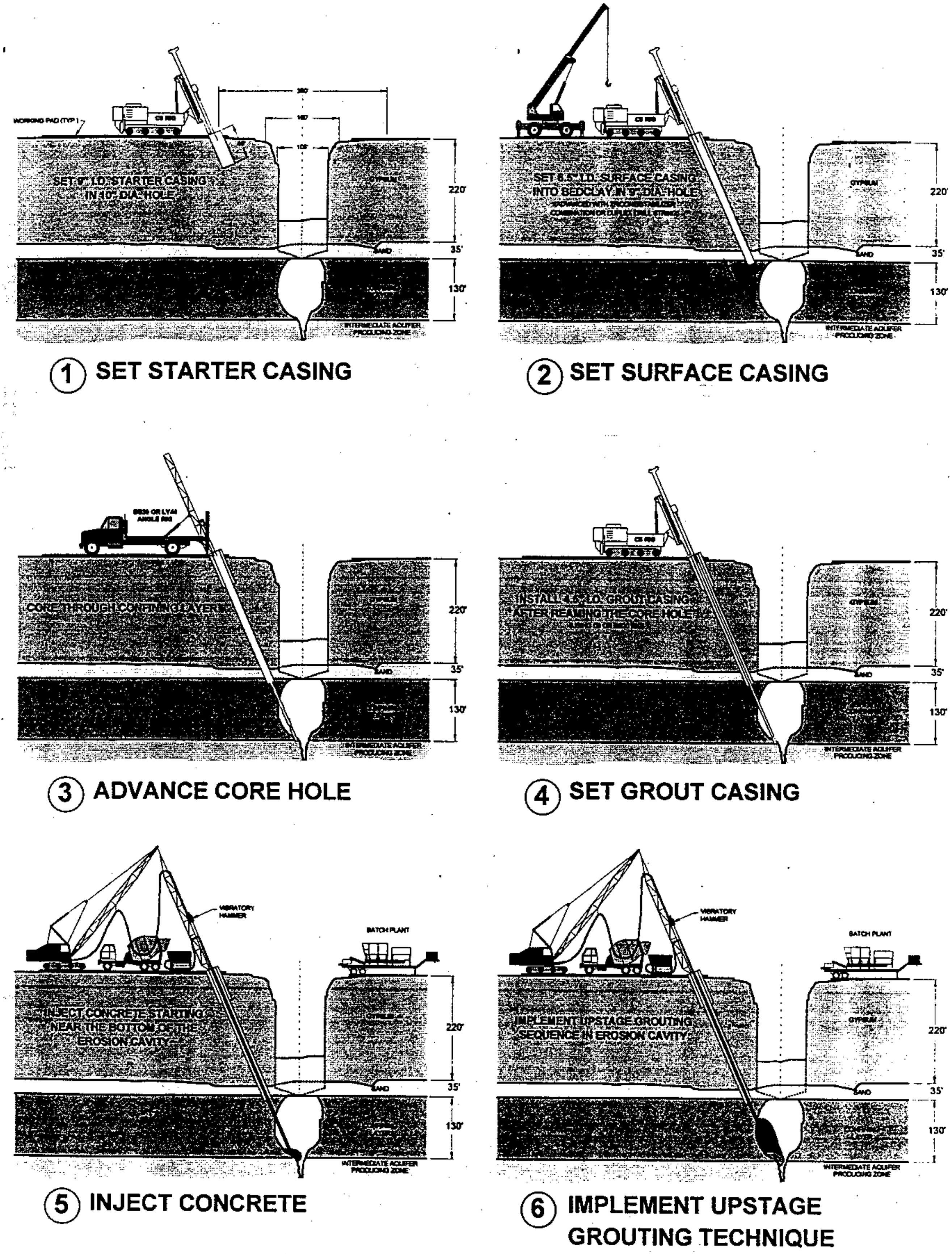


Figure 2. Zone of Capture of Production Wells
(as Documented on June 28, 1994 in Floridan Aquifer Monitor Wells)



① SET STARTER CASING

② SET SURFACE CASING

③ ADVANCE CORE HOLE

④ SET GROUT CASING

⑤ INJECT CONCRETE

⑥ IMPLEMENT UPSTAGE GROUTING TECHNIQUE

Figure 3. Drilling/Grouting Methodology

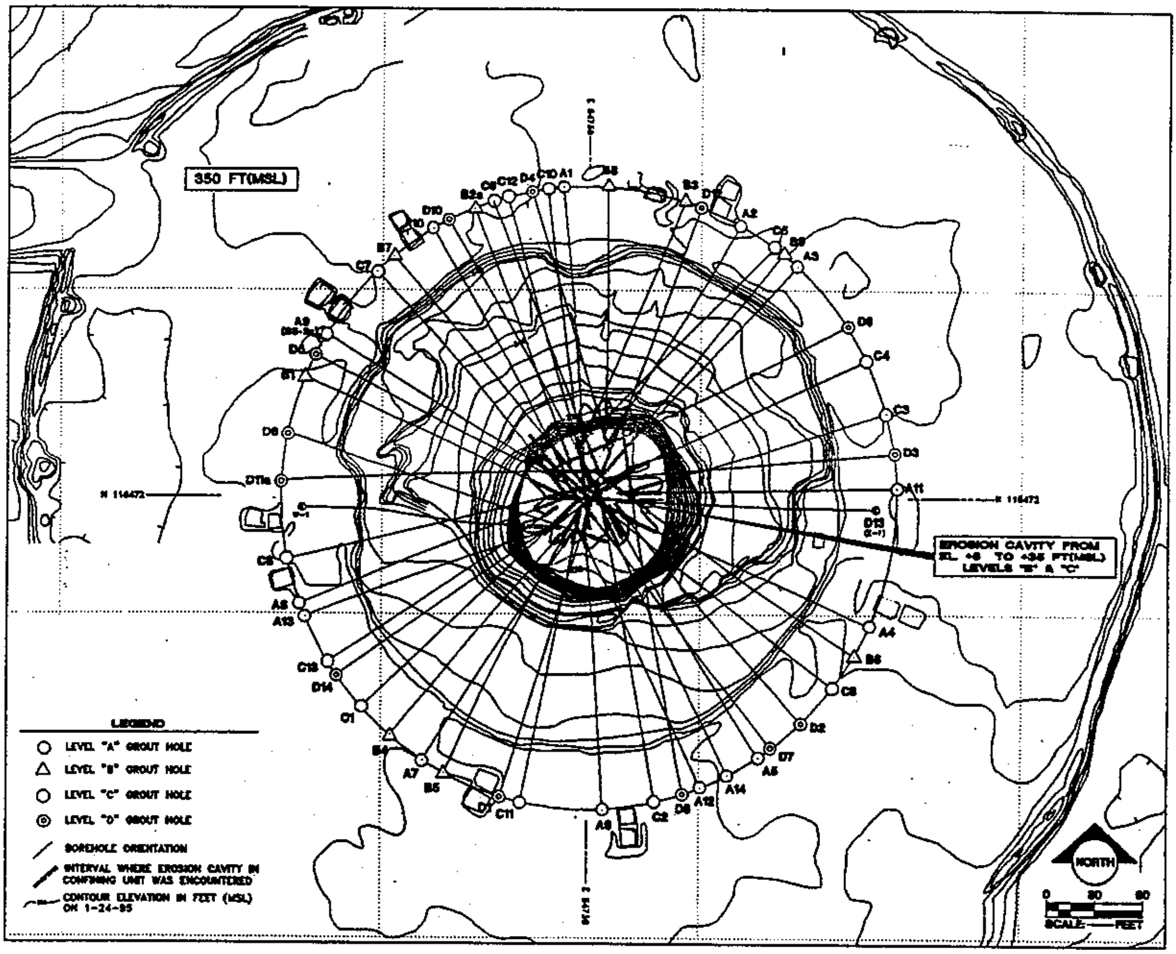


Figure 4. Grout Hole Location Plan

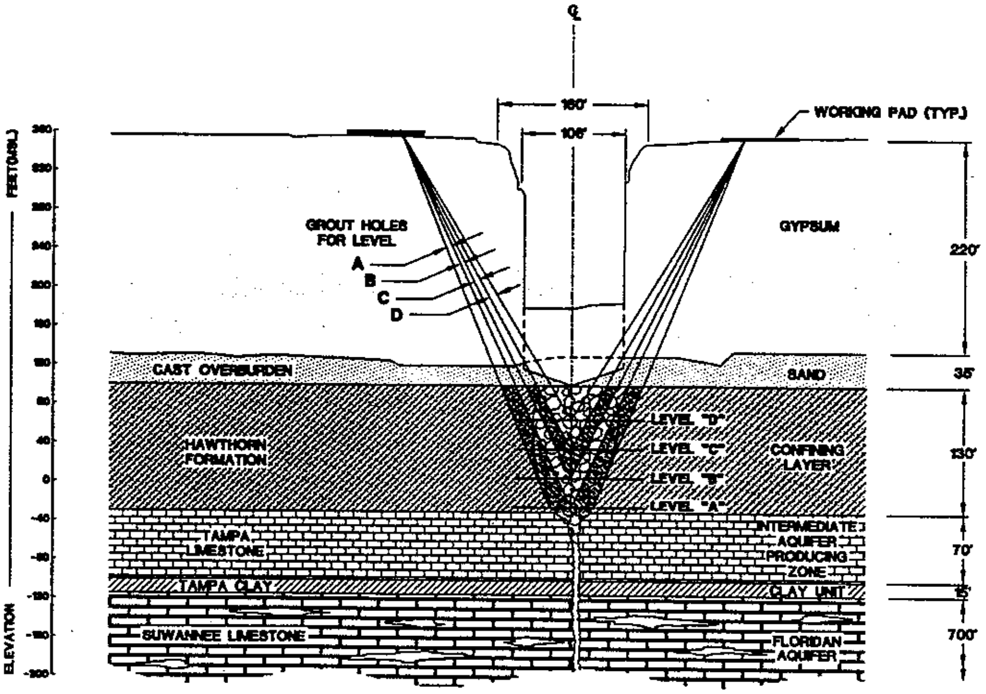


Figure 5. Cross Section Illustrating Target Grout Levels

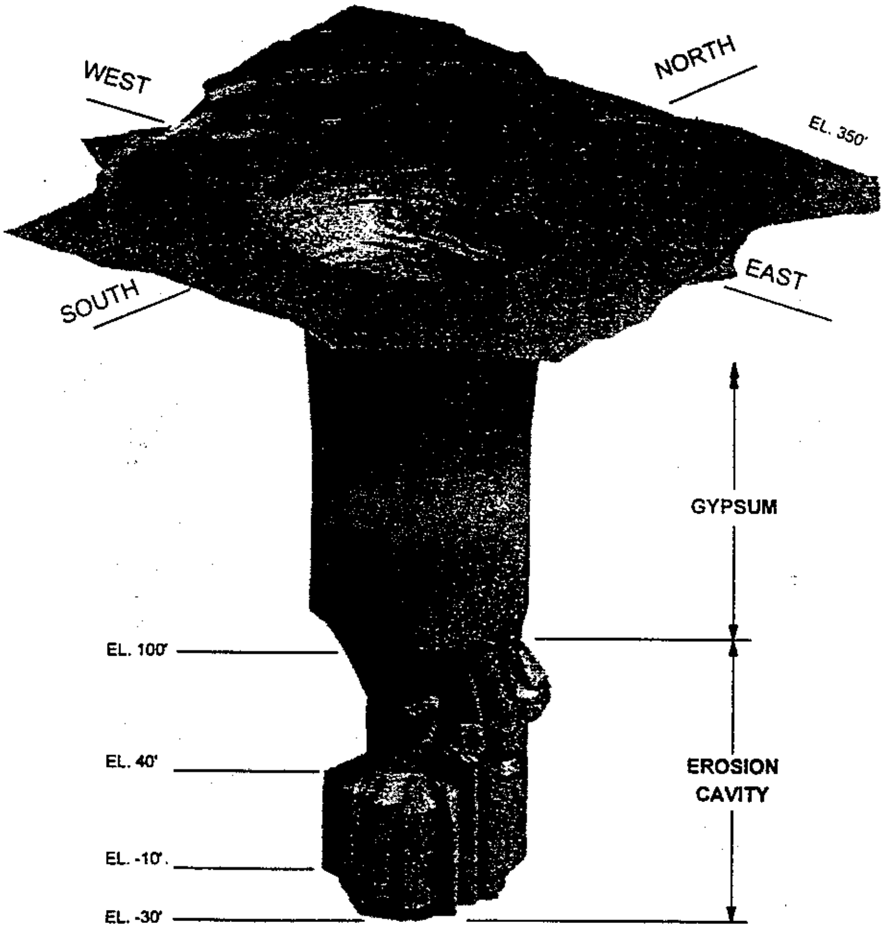


Figure 6. 3-D View of Erosion Cavity

Figure 7. Intimate Bonding Between Concrete and Gypsum

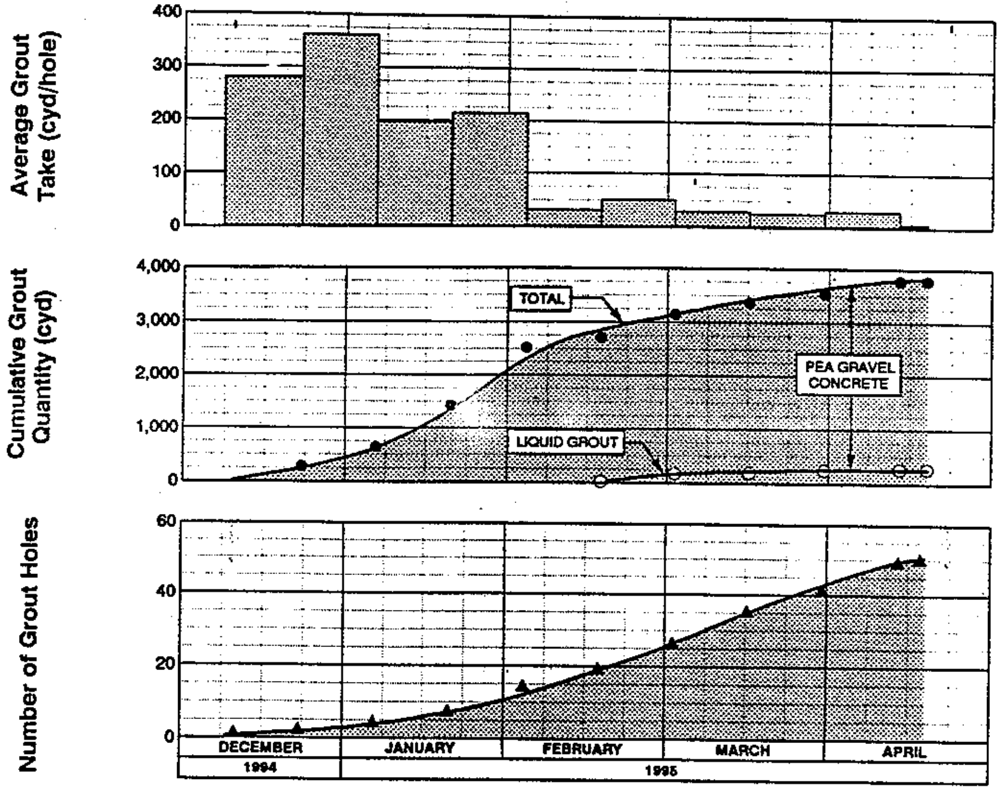


Figure 8. Chronologic Overview of Grouting Activities

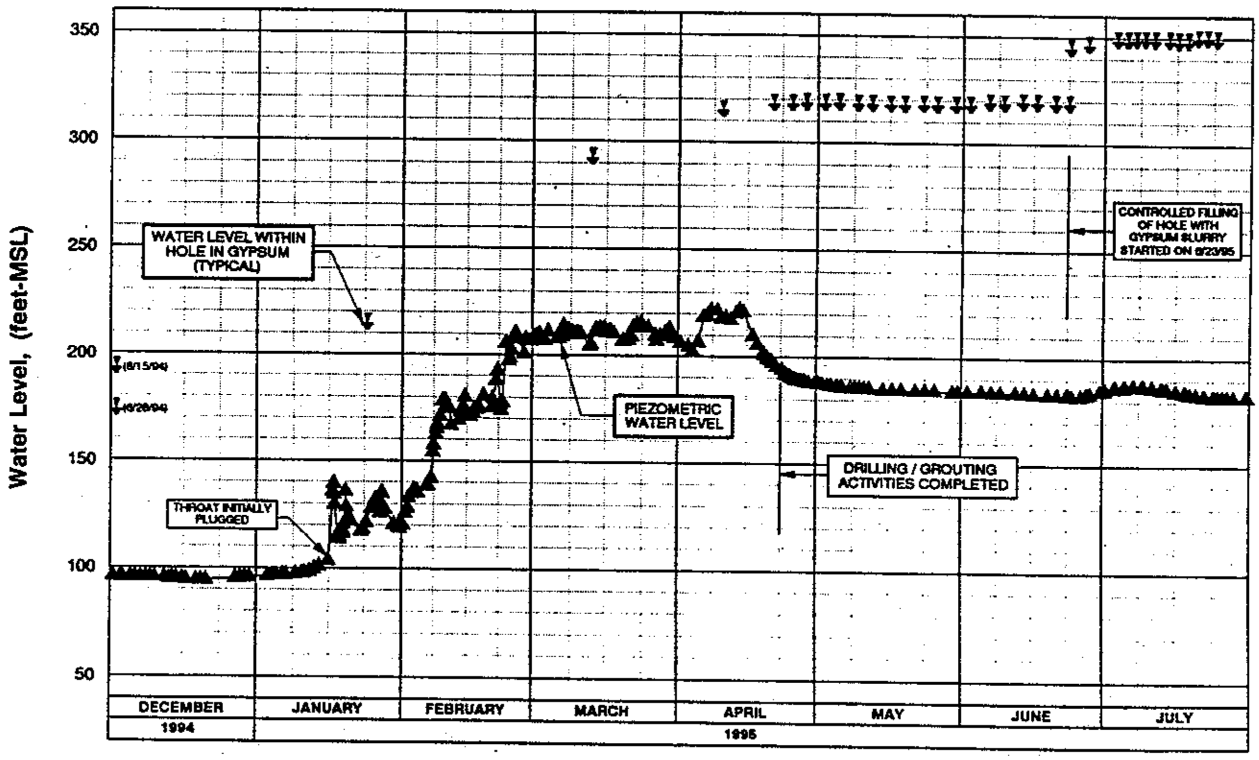


Figure 9. Piezometric Water Level in Upper Zone of Confining Unit Adjacent to the Sinkhole

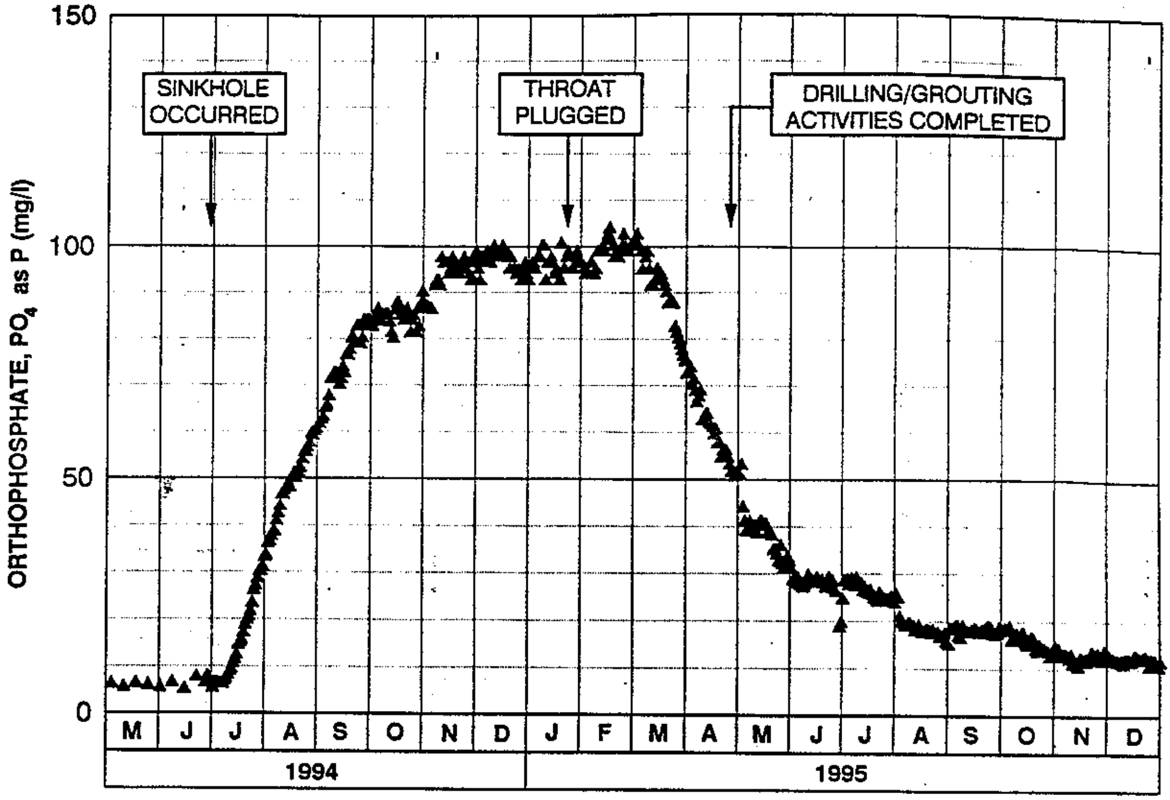


Figure 10. Water Quality In Production Well SF-1

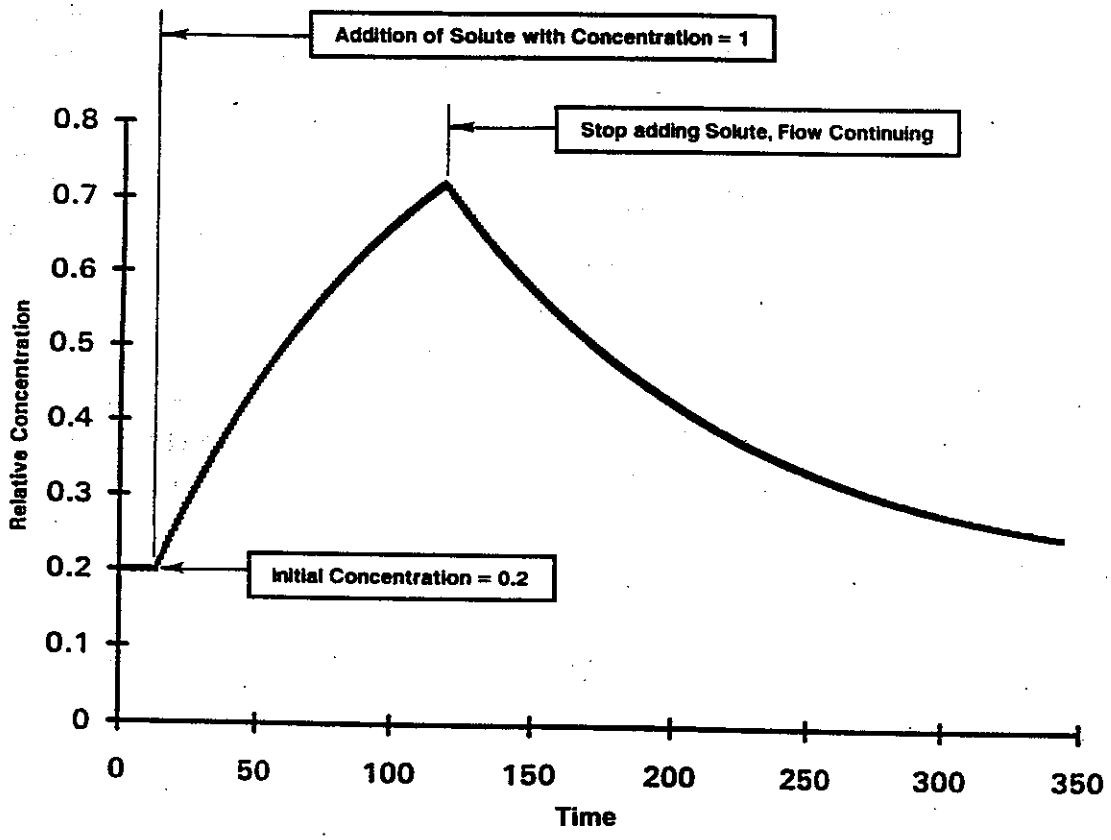


Figure 11. Relative Concentration in a Continuous Stirred Tank Reactor

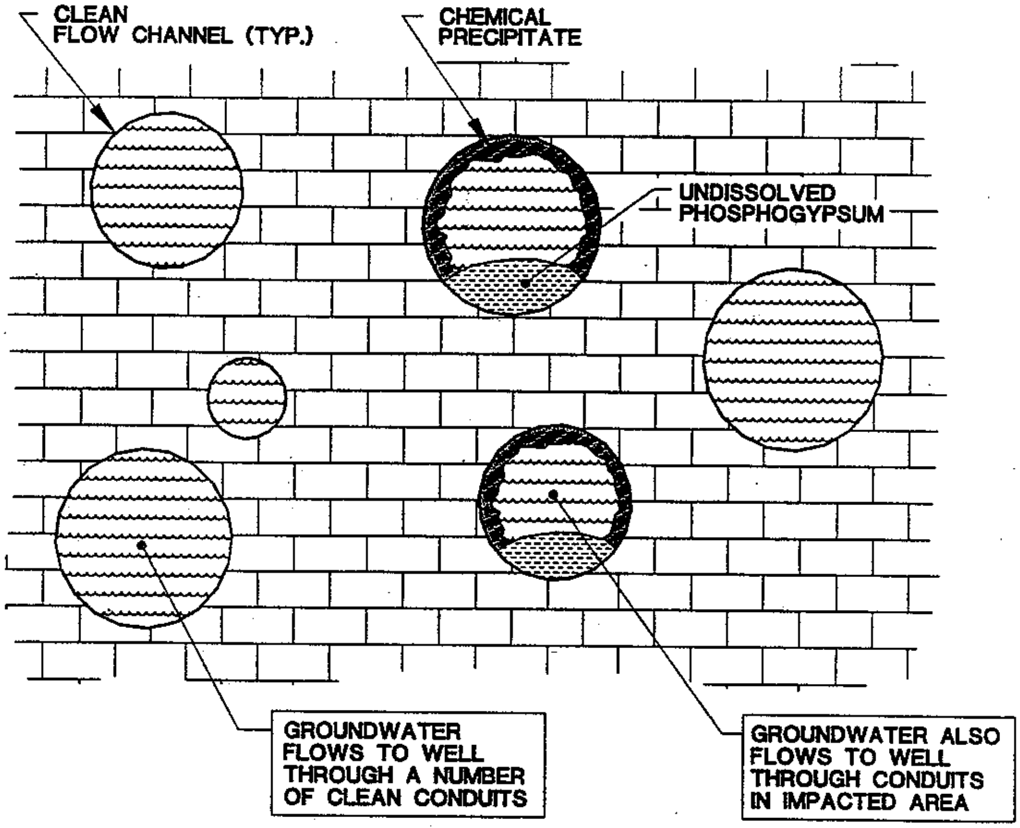


Figure 12. Flow Pattern Illustrating the Redissolution of Precipitates