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GEOLOGICAL IMPLICATIONS OF DEEP WELL DISPOSAL IN THE BAHAMAS

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ABSTRACT

In the Bahamas a variety of liquid wastes have been disposed of via boreholes for a number of years. The most common of these wastes include storm water, raw sewage, treated effluent, heated brine, and cooling water. A smaller, but no less significant component, comprise the by-products of various industrial and commercial enterprises some of which may be toxic. All constitute a threat to valuable groundwater resources.

The boreholes used range from 6 inch to 36 inch in diameter and from 50 ft. to 650 ft. in depth. The wells may be uncased, partly cased, or multi-cased, usually with steel or PVC cemented into place.

Over the years many wells have functioned successfully though there have been significant failures, which have led to serious subsurface pollution. Most malfunctioning wells can be attributed to casing failure, particularly as a result of corrosion.

Subsurface investigations have failed to reveal any shallow aquicludes in the Bahamas that could be used to prevent mixing between the wastes disposed of at depth and shallow freshwater lenses. Instead zones of high transmissivity are used as receiving zones, and it is assumed that wastes are rapidly mixed, diluted, and dispersed at these horizons, thereby nullifying any threat that they may pose to the environment. The zones of high transmissivity correspond to cavernous horizons that developed in the subsurface carbonates in relationship to low sea level stands and stratigraphic disconformites. Several such horizons occur in the Lucayan Limestone, but these vary in depth regionally. More widespread cavern zones occur beneath the base of the Lucayan Limestone and at depths that equate to the Pleistocene sea level lows. These are the main ones used for deep well disposal.

A good deal more research is needed on the character and fluid dynamics of these receiving zones as this means of disposal is providing an essential service in a situation where all other alternatives are considered too costly.

INTRODUCTION

Associated with development and urbanization is an increase in the production of wastes. Man's proliferation is accompanied by a proliferation of his wastes and the increase appears to be a geometric one as living standards rise. The wastes produced are both solid and liquid and there is an ever increasing problem of finding places to dispose of them. Many wastes present a threat to the environment and should be treated prior to disposal. Unfortunately, proper treatment is a costly procedure and so other less costly alternatives are constantly being sought.

One such alternative is the disposal of liquid wastes by means of wells. On a comparative basis, this is a cheap option, however, it is an option that conceals developments and situations can arise with serious future implications. Subsurface pollution is not just difficult to detect, it is even harder to rectify. Before wastes are injected into the ground, therefore, it is imperative that all aspects of this practice be fully understood and the geological implications are the most important considerations of all.

WASTE PRODUCTS AND WELLS

The most common liquid wastes disposed of via boreholes include storm water, wash-down water, raw sewage, treated effluent, cooling water, heated brine, and reject water from reverse osmosis or similar such plants. The storm water is usually fresh, but the others vary from being fresh to highly saline. Besides these liquids, there are smaller volumes of waste that are generated as the by-products of a number of industrial and commercial activities and some of these can be regarded as fairly toxic: examples include photographic laboratory waste, garage waste, laundry water, and even abattoir wastes, to name but a few. Almost all of the wastes constitute a threat to valuable ground water resources, the occurrence of which have been described by Little et al. (1977) and Cant and Weech (1986).

The boreholes used range from 6 inch to 36 inch in diameter and from 50 feet to 650 feet in depth. The majority are probably about 100 to 150 feet deep and very few exceed 300 feet. In general, the deeper boreholes receive the greater volumes of waste, the maximum being about 5,000,000 gallons per day. Storm water disposal wells may receive more than this, but there is no means of quantifying their use, and often these are fairly shallow and liable to fail in very heavy downpours.

Almost all disposal wells are cased, at least for the uppermost 20 feet or thereabouts. The main exceptions to this are the storm water drainage wells used in Grand Bahama which are often uncased. A few wells contain multiple casings, particularly those built with proper specifications.

The casings usually comprise steel or PVC pipe and there is often a cement grout emplaced between the outer casing and the borehole wall. Packers and annulus monitoring devices are rare.

In New Providence it is estimated that about 300 disposal wells are presently in operation, but there is no register of wells available and many will have been installed without a permit or similar form of authorization. Disposal wells are presently only common in New Providence and Grand Bahama. The wide spread use of disposal wells in these two Islands started in the early 1970's and has accelerated since that time.

Probably the most important disposal well in New Providence is the Malcolms Park well which was installed in 1971. This well is 20 inch in diameter and cased to 400 feet and open to 640 feet. The well has received some 2 to 3 million gallons of raw sewage per day from the city sewerage system and appears to have functioned successfully for about 4 years. In 1978, however, monitor wells around Malcolms Park clearly indicated sewage pollution at shallow horizons and it was surmised that the steel casing had failed as a result of corrosion.

Other wells have been known to fail for whatever reason, but in general it is rare that there is any means of monitoring the wells, and so the failure rate is unknown. There can be no doubt, however, that large areas of New Providence have been affected by subsurface contamination as a result of the existing disposal well practice.

THE ENVIRONMENT AND SUBSURFACE GEOLOGY

General

The Bahamas consists of a series of shallow marine banks that emerge locally above sea level, but are separated from one another by deep water. The banks which are usually less than 30 feet deep, are akin to submerged plateaux with steep sides. From sea level down to a depth of about 5 miles, the geology is dominated by limestone and with anhydride, salt, and gypsum, appearing at deeper horizons. Throughout the sequence, and particularly towards the surface, there are cavities and cave systems. The most dramatic examples of which are the picturesque blue holes that occur in places on the surface of the banks. Some blue holes exceed depths of 350 feet and one has been plumbed to more than 600 feet (Little et al., 1977). All of the larger Bahama platforms appear to be honeycombed by such cave systems and it is evident that they dominate the hydraulics of the limestone plateaux (Dill 1977). In Southeast Florida cavities are reported down to 6000 feet (Puri et al., 1973), and it is likely that this depth is exceeded in the Bahamas (Tator and Hatfield 1975).

Information on the subsurface geology of the Bahamas has been gathered by geophysical methods and drilling. Geophysical evaluation suggests that the igneous basement may be as deep as 7 miles and that the carbonate sequence extends down to about 24,000 feet. It is postulated that a clastic-evaporite sequence extends from 24,000 feet down to the basement. Five deep exploratory wells have confirmed that limestone and dolomite predominate to 18,000 feet and that clastic deposits start to appear at this horizon. Except for the five deep wells, almost no other drilling has been done below 600 feet, and no continuous cores have been obtained below 550 feet. The surface down to about 100 feet, however, has been thoroughly explored in the land areas because it is at this horizon that the ground water resources occur (Little et al., 1977).

Most of what is known about the stratigraphy below 100 feet is extrapolated from knowledge of the subsurface of Southeast Florida where there has been extensive investigation (Winston 1982).

There is abundant literature available on the unconsolidated sediments of the Bahamas, but very little has been published on the subsurface geology of the area. A few significant studies, however, have been made on cores that were collected by the Bahamas Government, the University of Miami, and various oil companies. These include the work of Supko (1970), Tator and Hatfield (1975), Little et al. (1971-1977), Cant (1977), Gidman (1978), Beach and Ginsburg (1980), Winston (1982), Pierson (1982), and Williams (1985). The subsurface geology outlined below has emerged from these studies.

The Lucayan Limestone

From the rock surface exposed on the banks down to a depth that varies as follows:

Andros and Great Bahama Bank	129 ft.
Long Island	114 ft.
San Salvador	96 ft.
Inagua	84 ft.
Crooked Island and Acklins	63 ft.
Grand Bahama and Abaco	63 ft.
Mayaguana	24 ft.

there is a limestone formation that has been named the Lucayan Limestone (Beach and Ginsburg 1980). It is a dull-yellow to buff pelloidal and ooidal limestone that is irregularly cemented and mottled in appearance. Usually the rock shows evidence of marine bioturbation, but fine bedded structures occur near the bank margins. Throughout the formation there are discontinuity surfaces that are interpreted as horizons of subaerial exposure. The evidence of exposure includes laminated crusts, burnt limestone fragments, fossil soils with land snails, and karstic solution features. Since the banks are subsiding (Banks 1967), the horizons of subaerial exposure must result from low stands of sea level. The units between the discontinuity surfaces correspond to periods of sedimentation when sea level was high. Horizontal cavern systems relate to the discontinuity surfaces the presence of which is often inferred in cores when there is little or no recovery. There are at least 12 discontinuity surfaces in the Lucayan Limestone and some of these are laterally so extensive that they can be used as marker horizons to correlate between the banks. Beach and Ginsburg (1980) report that these surfaces occur on average every 6 feet in the upper 30 feet of the formation and every 10 feet below that level. Pierson (1982) has suggested that the thickness of the Lucayan Limestone is controlled by regional folding and that the great Bahama Bank lies in the center, where subsidence has been highest.

Deeper Formations

Below the Lucayan Limestone the rock changes to a poorly stratified skeletal packstone with common megafossils and thick accumulations of coral and coralline algae near the margins. Besides the change in sediment composition, which is very rapid and widespread, there is also a change in the frequency of discontinuity surfaces. On average these now occur in every 15 feet of core. Other significant changes include the random, appearance of dolomite and the coral Stylophora. Stylophora became extinct in the western Atlantic area at the end of the Pliocene, and therefore, the evidence suggest that the Lucayan Limestone is Late Pliocene to Late Pleistocene age, or, equivalent to the onset of the classic glaciation in the Northern Hemisphere (i.e. ranging from 11,000 to 3,000,000 years in age approximately).

The formations beneath the Lucayan Limestone have not been studied in any detail in the Bahamas. None-the-less the 550 feet core from San Salvador was described by Supko (1970) but it is uncertain how representative this is for any of the other banks particularly the larger ones, and the description is largely petrographic giving little attention to cavities and similar features that affect the hydraulics of the banks. In the San Salvador core there is a breeciated paleosol from 90 feet to 110 feet and from 133 feet down to 493 feet the rock is almost pure dolomite. The thick paleosal suggests a long period of surface exposure (perhaps the onset of glaciation), and the dolomite indicates large scale limestone alteration in a ground water environment that was probably fresh or brackish. A number of discontinuity surfaces can be identified in the sub-100 feet sequence, each of which may be associated with lateral cavern systems.

GROUNDWATER AND HYDRAULICS

Two significant factors regarding the geology and pre-history of the Bahamas impart fundamental controls of the hydraulics of the Bahamas. One is that the banks are made up of marine formed sediments, which are unstable under atmospheric conditions and the other is that there were dramatic fluctuations in sea level during the Pleistocene which exposed these sediments to meteoric conditions. World-wide research has revealed that sea level fell 400 to 600 feet lower than it is at present at the height of the periods of ice advance. It is also known that there were several such advances and in fact sea level fluctuated quite rapidly for more than two million years.

During the low sea levels all of the banks would have been exposed forming high limestone plateaus. Rainfall on the plateaus would have drained away internally, via solution sink holes, until the water table was met, at which point the flow would become more laterally orientated. The vertical phase of flow occurring in the vadose zone would have induced the development of such features as the blue holes, which were already referred to, and the horizontal flow of water in the phreatic zone would have aided in the creation of cavern systems that were horizontally aligned. Because these low sea stands occurred over a wide range of levels, cavern systems could have developed at many difference depths. Longer periods of stable sea level will have created larger more effective caverns particularly if the sea levels reoccurred at the same horizons.

The net effect of the above is that the Bahamas Banks contain cave systems that allow massive volumes of water to flow through them. In other words ocean currents and tides can actually pass through the rock. The movement of this water is concentrated at horizons of ancient sea levels, and the fact that the ice ages resulted in several long periods of sea level low, between depths of 400 and 600 feet, implies that there should be good water movement and caves between these depths. The surface of the Pliocene formations (i.e., the rocks beneath the Lucayan Limestones) were also exposed for a long time and so this horizon should also be cavernous.

The degree and effectiveness of hydraulic connection of a particular subsurface horizon to the ocean is easily proven. For example water in a hole drilled to a particular depth, presumably deep, will have tidal responses that are more closely attuned to the deep ocean as opposed to the local water table, or even the sea on the banks. This was demonstrated in deep holes on Long Island that gave tidal responses that were greater than, and in advance of, those of a tide gauge that was actually positioned in the sea on the west side of the island. This evidence indicates that sea water could pass through the subsurface more easily than it could over the banks. Further evidence of this phenomena is demonstrated by Blue Holes that are out of synchronization with local tides and sometimes these give rise to quite dramatic effects, for example whirlpools, or "fountains". The fact that the Bahamas appears to have an inverted geothermal gradient is also evidence that the deep subsurface is hydraulically linked to the ocean.

Effective hydraulic connection to the sea is obviously a limitation to the development and preservation of freshwater lenses, in an oceanic island, since these lenses are little more than entrapped bodies of rainwater. Easy access of saline water will flush them away. It is significant that the thickness of freshwater lenses on many Bahamian islands is strongly controlled by a particular subsurface horizon. These controls have been described in detail by Cant and Weech (1986), and good examples occur in Andros, Grand Bahama, and Abaco, where freshwater is limited by the base of the Lucayan Limestone, and New Providence where lenses are widely restricted to the first discontinuity surface known locally to drillers as the "Hard Brown Crust". No freshwater lenses are known to extend below the base of the Lucayan Limestone and therefore, this horizon indicates that there is a significant change in rock characteristics at this level. It explains why a land area like North Eleuthera can possess a thicker freshwater lens than either Grand Bahama or Abaco even though the latter are larger land masses and receive greater rainfall. In this context the Lucayan Limestone must be regarded as the freshwater aquifer of the Bahamas, though of course in many areas, particularly in the smaller islands, it may contain salt water.

WASTE DISPOSAL AND RECOGNITION OF DISPOSAL ZONES

The movement of large volumes of salt water through the subsurface, with eventual discharge to the sea, provides an ideal situation for liquid waste disposal. If the unwanted liquid wastes can be injected into a horizontal cavern system with a high hydraulic efficiency, they are rapidly diluted and dispersed, and then carried away to an open sea outfall which is well removed from human activity. The most important requirements are that the wastes be put into adequate cavern systems (disposal zones), and that important overlying aquifers are not contaminated. Obviously one important consideration must be well design, but it is equally important that the geological controls be properly evaluated.

The ideal situation arises where a cavernous formation is overlain by a totally impermeable one, but unfortunately in the Bahamas there are no impermeable formations, or at least none near to the surface. Some horizons are highly permeable and some are not, and again there is something of a wild card situation created by the widely dispersed vertical solution systems.

In Southeast Florida where subsurface waste disposal is fairly well regulated, and geological conditions are relatively similar to the Bahamas, there are recognized waste disposal zones extending down from 2950 feet in a horizon known as the "Boulder Zone", which is approximately 1000 feet thick. The Boulder Zone comprises a highly cavernous dolostone and contains water similar in chemistry and temperature to that of the bottom of the Florida Straits, which implies an effective hydraulic connection to the sea. Some of the caverns in the Boulder Zone are reported to be as much as 90 feet in depth. Above the Boulder Zone, in rocks of Miocene Age, there is a 700 foot section of clays and marls that is supposed to be confining and therefore provides a protective barrier to the Biscayne Aquifer above, from which potable supplies are obtained.

Other cavernous zones have been located in Southeast Florida at shallower and deeper depths, but these are not used for waste disposal. Some contain brackish water and are being conserved for future demineralization, where as others are intended for other purposes, such as providing a source of water for heat exchange purposes, or even storage of treated effluent for future use. Drilling evidence suggests that the caverns have a broad horizontal distribution and that there is practically no vertical connection.

In the Central Bahamas the Boulder Zone horizon probably occurs at a depth of 4000 to 5000 feet., and it is interesting to note that a large number of limestone caves were reported in the Long Island well at a depth of 4600 feet. Other than the 5 deep oil exploration wells no other penetrations have been made to this level in the Bahamas and so little is know about it - in any case the horizon is thought to be too deep to be used as a practical waste receiving zone.

Theoretical considerations suggest that there should be a well-developed horizontally aligned cavern system at depths ranging from 400 to 500 feet. These would have formed during the periods of low sea level, but unfortunately they also demarcate the base of the vertical solution system and so low density wastes could possibly migrate from them to the surface. No impermeable horizons are recognized in the subsurface of the Bahamas though drillers logs sometimes refer to them. Fine-grained dense limestones and dolostones may appear impermeable in a hand specimen, but the formation would still contain a solution network that would allow liquids to pass though. On this basis one is forced to accept the fact that there are probably no "ideal" disposal zones near the surface in the Bahamas, and economic constrains make it impractical to go to deeper levels where such horizons might occur. The only way in which the problem can be bypassed is by ensuring that the wastes are put into rock formations with very high transmissibilities so that there is rapid mixing and dispersal of the effluent and less likelihood of a stationary waste plume developing. An entrapped plume of waste could easily migrate upwards if it is less dense than the surrounding ground water and this is usually the case where sewage effluent is concerned.

Assuming that there are no effective confining layers present in the shallow subsurface it is clear that waste disposal must be made to highly cavernous zones. This means that large volumes of waste should be put down to the 400 to 600 foot level and even modest quantities should go below 100 feet. The Lucayan Limestone must be regarded as the Bahamian aquifer and should be protected in similar fashion as the Biscayne Aquifer. Unfortunately every septic tank discharges effluent directly to the water table and almost all disposal wells discharge into the Lucayan Limestone. The existing Building Code should be amended to specify minimum depth requirements, so that in time all disposal wells are cased through the Lucayan Limestones and double cased through any freshwater resources. Wells into which more than 1 million gallons per day are discharged should take the liquids below 400 feet (i.e. should be cased to 400 feet), and quantities that are large, but less than this can be proportioned between casing depths of 200 feet and 400 feet. For example, a 500,0000 gallon-a-day well should be cased to 300 feet and the range of open hole discharge should be at least half that again of the casing depth, i.e. a 300 feet cased well should have 150 feet of open hole beneath the casing.

One aspect that is important, but has not had the attention it should is the fact that subsurface saline water which is used for heat exchange purposes, and demineralizing, is usually obtained from below 100 feet, i.e. beneath the Lucayan Limestone. Disposing of large quantities of liquid waste at this horizon would make the water at this level unfit for either purpose and therefore, there is strong justification for preserving a saline horizon for future use. For this reason it is suggested that any disposal well discharging more than 100,000 gallons per day should be cased to 200 feet. The 100 foot to 200 foot level could provide saline water for whatever future needs there may be.

For the time being the above must be regarded, at best, as uncertain guidelines which should be modified as more drilling information becomes available.

OTHER CONSIDERATIONS

Earth Movements

Any geotectonic activity must constitute a threat to deep well disposal as it could result in well casings breaking or splitting, and lead, in turn, to contamination of the aquifer. Most people assume that the Bahamas Bank area is tectonically stable, however, there is a wealth of evidence that indicates that earth movements have occurred in the region in recent geological time.

Scheidegger (1977) evaluated join patterns in surface rocks of the Bahamas and obtained a stress pattern that supported the idea that the North American tectonic plate is being dragged westward from the Mid-Atlantic Ridge and is therefore in a state of internal E-W stress relief. On this basis there is a potential threat, but it is hard to evaluate, in human terms, as most of the evidence has been obtained from rocks that are 125,000 years old. It is also possible that the jointing evident is a surface phenomenon only, and therefore presents no threat to deep wells. One deep well at the Blue Hills desalination plant is known to have malfunctioned because its steel casing sheared. The actual break was photographed, but it was not possible to ascertain if it was due to earth movement or poor installation.

In general, there are no measures that can be taken to prevent casings from breaking as a result of earth movement. If the rock itself is fracturing, then plastic or steel will also break. The only solution to the problem is to ensure that the integrity of the casing is monitored so that those using the well will know when there is a casing failure.

Well Design

It is beyond the scope of this report to provide detailed specifications of well design, except with regard to recommended well depths and casing levels, which are given at the end of a previous chapter. Besides those guidelines, a few other suggestions are listed that are worth considering whenever a deep disposal well is being installed.

Casings: raw sewage and salt water can create acidic solutions that corrode metallic components. In these circumstances plastic piping should be used or similar resistant material. If the casing needs to be strengthened, then this can be achieved by means of outer casings and grouting. As a rule, all wells should be double cased through fresh or brackish water horizons. If toxic wastes are to be disposed of by means of a deep well, in an area where there is an important ground water resource, then the annulus between the casings should be used as a means of monitoring for casing failure. There are several methods by which this can be done and these are described in literature that is available.

Monitoring: as mentioned above, the annulus between two casings can be used to monitor the integrity of the casings, however, aquifer contamination can result from more than casing failure and therefore another means of monitoring is needed when it is essential that ground-water should not be polluted. In this circumstance isolated, purpose built, monitor wells are required. These should be installed to depths that will give significant meaningful information, and spaced out to provide the same. To reduce drilling costs a single well can be used for multi-level observation, if properly designed with a number of inner casings that open out to different depths. Unfortunately, karst hydrology results in erratic and unpredictable movement of ground water, and so serious pollution can occur via a fissure system that is undetected by a monitor well network. The development of a massive waste plume however, should be detected in the well sampling results.

Liquid wastes: the precise composition of the waste being disposed of is an important consideration that should play a part in the design requirements of any disposal well. For example certain waste substances may require treatment before being injected into the well, and an obvious example is heated acidic liquid which is liable to eat away the groundrock to create a variety of problems. Similarly some wastes may contain too many solids that are too large and these could lead to blockages in the disposal zone or well. In this case screening is necessary.

In contrast to the two cases given above, there may be some justification in not lining the disposal well at all. For example a storm water drainage well could be used as a means of artificial recharge, and therefore, should be open from the water table down. Casing a drainage well down to saline horizons results in the loss of potential recharge.

Disposal Well Operation

Many people live in parts of the world where a deep well will not accept injected waste, or, where the well may even eject water as in artisan situations, and so brief mention should be made as to how these wells operate. In principal it is quite simple: the wells simply link the land surface to cavern horizons that open out into the sea. On this basis they act as drains and will continue to work as long as they do not become blocked, and as long as there is enough free head available to ensure that flow is maintained towards the sea. Problems arise where there is poor hydraulic connection to the sea and where the water table periodically rises to cover the level of discharge. The fact that freshwater floats on seawater, tends to add a little confusion to the situation in Bahamian Islands because it means that the head component must be measured relative to the local water table, and not sea level itself. If head were effective relative to sea level and if the Ghyhen-Hertzberg principal were not influential then one would expect the top of the freshwater lenses to drain down into the sea via the deep blue hole system.

CONCLUSIONS

(a) Deep disposal wells can work in the hydrologeological environment of the Bahamas.

(b) The most important requirements are that acceptable liquid wastes be conveyed to adequate receiving zones, without leakage in transmission, and without blockage.

(c) If there is any chance that water resources, fresh, brackish, or saline, may be polluted then measures should be taken to see if and when this happens.

(d) At present there is not enough subsurface information available to be certain where wastes are going. Exploratory drilling is needed in conjunction with proper geophysical logs.

(e) Many disposal wells in current use are too shallow, and have not been built to adequate standards.

(f) Major disposal systems often rely on one well only and so use of the well continues even when the well has failed.

(g) The Building Code and equivalent rules are not strict enough to protect the subsurface from pollution.

RECOMMENDATIONS

(a) Studies should be made to establish recognized waste disposal zones in the subsurface of the Bahamas. These studies will require exploratory well drilling, coring, and geophysical logging.

(b) Once accepted disposal zones have been identified, a full range of specifications should be established to control all aspects of deep well disposal. These will include such items as well depths, well head installations, casing requirements, pretreatment, and subsequent monitoring. The specifications should be enforced by the Building Code, and appropriate legislation.

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