

SECTION 1

Investigation and Evaluation of Surface and Subsurface Drainage

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Hydrogeologic Investigations for Mine Dewatering

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ABSTRACT

Mine drainage involves a wide variety of ground-water problems but evaluation techniques usually focus on common goals. The determination of reliable aquifer coefficients--the transmissivity or the hydraulic conductivity and the coefficient of storage--together with knowledge of the aquifer geometry and the nature of boundary conditions, as determined by field exploration and testing methods, forms the basis for effective planning of mine dewatering systems. The recent advances in aquifer modeling on digital computers have increased the hydrogeologist's ability to provide reliable quantitative evaluations in the complex geologic settings generally involved in ore-body environments.

Case examples of common aquifer and boundary conditions, including a cement-limestone quarry in Missouri, a complex of lead-zinc open pit mines in the Northwest Territories of Canada, and the Athabasca Tar-Sand mining area of northern Alberta, are cited to demonstrate the diversity of mine ground-water problems and the commonality of approaches to their solution. Early integration of dewatering programs with the exploration, geotechnical, mine planning and operational efforts can have significant economic benefit.

INTRODUCTION

Mine drainage, in the ground water sense, refers to the dewatering or depressurization of water-bearing formations--aquifers--that may occur over, under or within the material being mined or quarried. Such drainage is done for a variety of reasons that start and usually end with economics, but include absolute mining feasibility, operational efficiency, slope stability, and safety.

The hydrogeologic evaluation of ground-water problems may not be difficult if the geology is clearly understood. Many situations, however, require extensive testing and even then, some cases become evaluations of flooding probability rather than reliable projections of ground-water control. Solid rock aquifers or aquitards, in which water movement is through fractures, joints, faults or solution openings, tend to be the most difficult to evaluate. Unfortunately, it is a fact that the investigations of many mining prospects concentrate so intently on the ore that the potential for mine drainage problems is neglected until late in the planning or even into early development stages.

Few areas of hydrogeology offer the diversity of problems encountered in both surface and underground mines. The very nature of many ore bodies, being anomalous concentrations of the desired mineral, often brings out unique hydrogeologic behavior that must be understood to achieve the required ground-water control. Greenslade, Brittain and Baski (1) recently referred to underground mine dewatering as "The Anatomy of Anomalous Conditions"--a beautiful title that says much about the interface of art and science in mine dewatering. Mines and quarries occur in developed and remote areas, both of which may be regarded as hostile environments for differing reasons. The rapid proliferation of environmental and safety laws has had an impact on mine drainage practices. Extremes of climate are another element of variable but often critical impact on mine dewatering systems.

Nevertheless, the evaluations of mine ground-water problems almost always have in common the determination of certain properties of the water-bearing formation or formations and their hydrogeologic environment. In brief outline, these include:

1. Aquifer Coefficients. Transmissivity (T) is a

measure of the ability of the entire thickness of a unit of aquifer to transmit water from place to place in response to a unit gradient. It is the algebraic product of the coefficient of permeability (or more recently, hydraulic conductivity) and aquifer thickness. The Coefficient of Storage (S) represents the amount of water released from (or added to) storage in the pore space of a unit volume of rock in response to a unit of head change. Reliable values for these coefficients permit mathematical projections by standard equations of aquifer behavior in response to pumping. Particularly important in many mining situations is the degree of uniformity of these properties--vertically and horizontally within the area influenced by mine pumping.

2. Boundary Conditions. Boundary conditions include sources of recharge, such as surface water bodies or leakage through other formations, or barrier boundaries such as impervious valley walls, which represent no-flow or lesser flow conditions in part of the affected area. A pervasive but commonly exaggerated concern in mining situations is recharge conditions that are improperly understood or are perceived as changing dramatically as the result of excavation.

3. Local Water Budget. The local water budget of an aquifer or aquifer system refers to the long-term allocation of the available inflow water--from precipitation, regional flow or recharge sources--to components of natural or artificial discharge. The goal of a water budget is generally to determine the perennial or seasonal replenishment that a mine drainage system will have to handle after a requisite amount of local aquifer storage is depleted. In many instances, the water budget analysis is critical to the long-term water supply available to the ore upgrading plant.

The necessary data are obtained by literature search, integration of available mine exploration data and, most importantly, by field testing of the aquifer. Aquifer coefficients can be estimated from laboratory tests and boundary conditions can be approximated if sufficient geologic detail is known, but the most reliable data for projecting aquifer performance are obtained by controlled pumping tests. The planning, execution and evaluation of such tests, and the determination of the adequacy of the resultant data are among the principal contributions of the hydrogeologist.

By a few case-history examples, this paper will attempt to demonstrate the diversity of mine dewatering problems and the commonality of the analytical approaches to their solution.

DUNDEE CEMENT COMPANY, MISSOURI

The situation of a mine or quarry in close proximity to a large surface-water body recurs frequently, with many interesting variations. The potential hazard of a nearby source of virtually unlimited recharge is apparent to even the untrained observer. Nevertheless, many mines operate successfully with small separating distances from a lake or river, at working levels substantially below the surface water elevation. Loofbourow (2) said it well: "Loss of life, property and production from flooding is grim, yet scores of mines have worked safely for generations under ground-water reservoirs, lakes and even the sea." Examples from the author's experience include limestone quarries in northern Michigan working within two thousand feet of Lake Huron, Lee Creek Mine on the edge of the Pamlico River estuary in North Carolina and underground lead-zinc mines of the Pend Oreille district in Washington where a hydroelectric reservoir impounded 50 feet of water directly over the mine workings.

These mines succeed from the mine drainage standpoint because the local geology provides a combination of aquifer coefficients and boundary conditions that limits the passage of the surface water to the working area. After the fact of successful operation, the retrospective analysis of why the flood was held out is easy. Without the benefit of after-vision, the hydrogeologist must evaluate the information available, which commonly is a fragmental by-product of ore-zone exploration, and devise a testing program.

Dundee Cement Company was erecting a premium-quality cement plant in Clarksville, Missouri when an artesian sand and gravel aquifer was discovered that might have provided a conduit for Mississippi River water to enter the limestone quarry adjacent to the plant. The situation is illustrated by figure 1A, in which the cement plant and the limestone quarry can be seen in the valley of Calumet Creek and by figure 1B, an idealized section across the valley. The planned quarry location was 4000 feet from the Mississippi River edge.

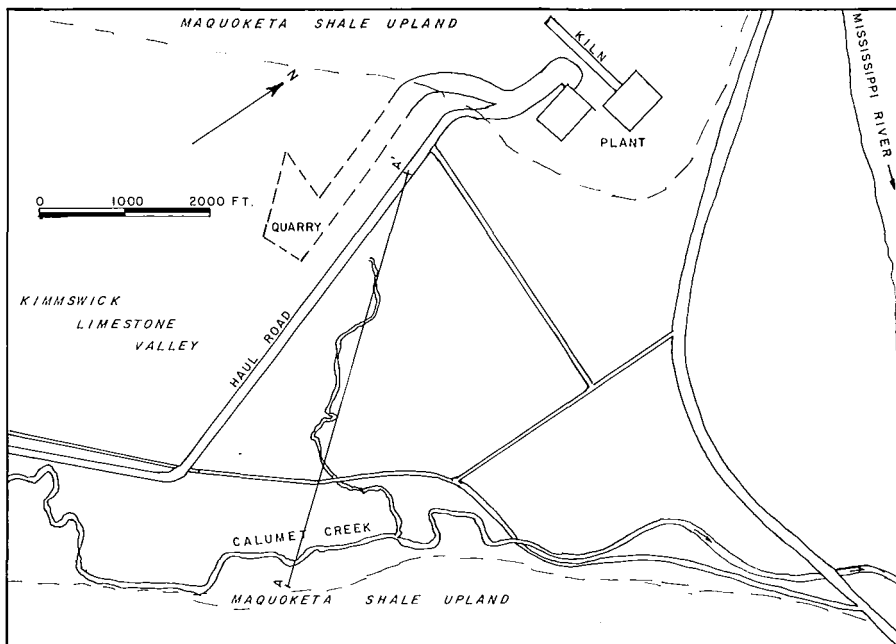


FIGURE 1A - LOCATION OF DUNDEE CEMENT CO. PLANT AND QUARRY, CLARKSVILLE, MISSOURI

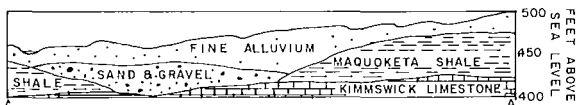


FIGURE 1B - GEOLOGIC SECTION A-A'

When geophysical exploration and a number of drill holes indicated the presence of an alluvial sand and gravel aquifer directly above the Kimmswick Limestone, there was concern that a large-scale dewatering operation or perhaps even an impervious cut-off wall might have to be considered. The sand and gravel, where encountered, ranged from 9 to 36 feet thick, overlying the limestone encountered at depths of 58 to 94 feet.

A test production well and a pattern of observation wells, as shown by figure 2, was drilled between the planned quarry and the Mississippi River. The wells showed that the aquifer was of variable thickness, ranging from 7 to 30 feet, with a generally lens shape thinning toward the valley sides, conforming to the earlier exploration. However, the well completion data indicated that the aquifer was less permeable than the earlier work had suggested. The test production well and the observation well were completed with well screens and developed until clear water was produced.

The test production well was pumped at 125 gpm for two

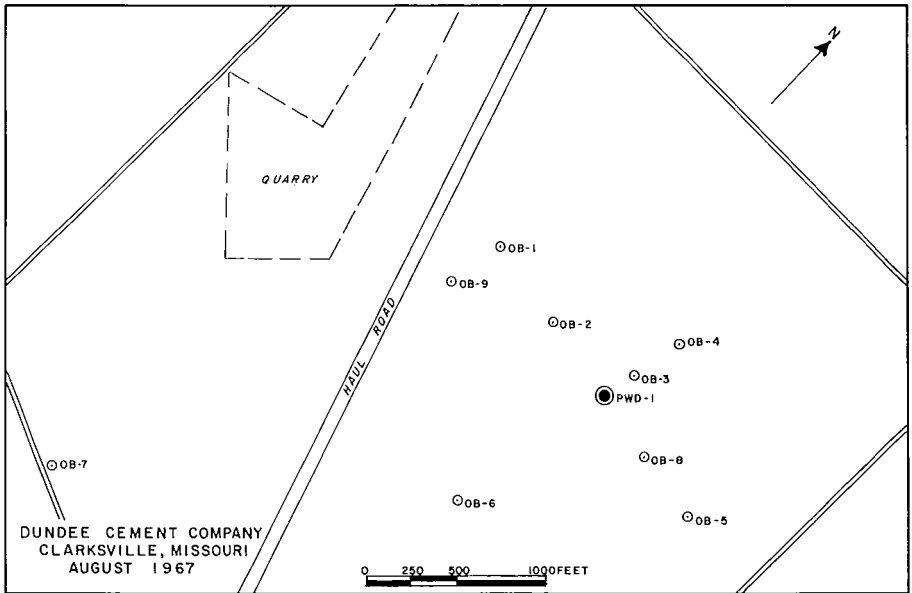


FIGURE 2 — AQUIFER TEST PATTERN

days and then, when the pumping level reached the well screen, the rate was reduced to 100 gpm for 2 more days. Typical semi-logarithmic drawdown graphs for observation wells are shown by figure 3. It is clear from these plots that no significant river recharge was encountered and that barrier boundaries, as indicated by the gradual down-turning of the drawdown graphs, were the dominant influence on the pumping tests. Analysis of the early drawdown data by the Theis log-log method (3) gave transmissivity values of 5000 to 17,000 gallons per day per foot, and averaging about 8000. Coefficients of storage were in the range of 0.00006 to 0.00008.

The drawdown-distance data, shown on semi-logarithmic coordinates by figure 4 indicated the impact of the barrier boundaries and the apparent large area of significant drawdown influence.

These results were confirmed by a second pumping test in the immediate vicinity of the planned quarry, with three test production wells intended as part of the permanent dewatering system.

The aquifer transmissivity, width and flow gradient demonstrated that the underflow down the Calumet Creek valley was on the order of 150,000 gallons per day. It was

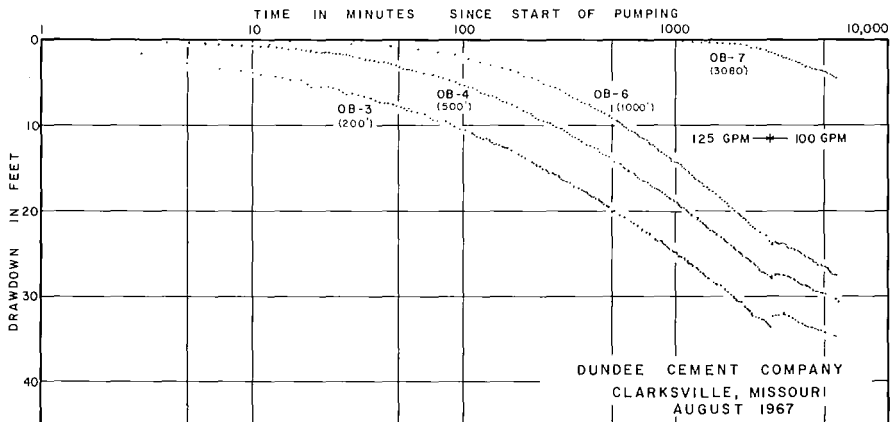


FIGURE 3 — OBSERVATION WELL DRAWDOWN CAUSED BY PUMPING PWD-1 AT 125 AND 100 GPM

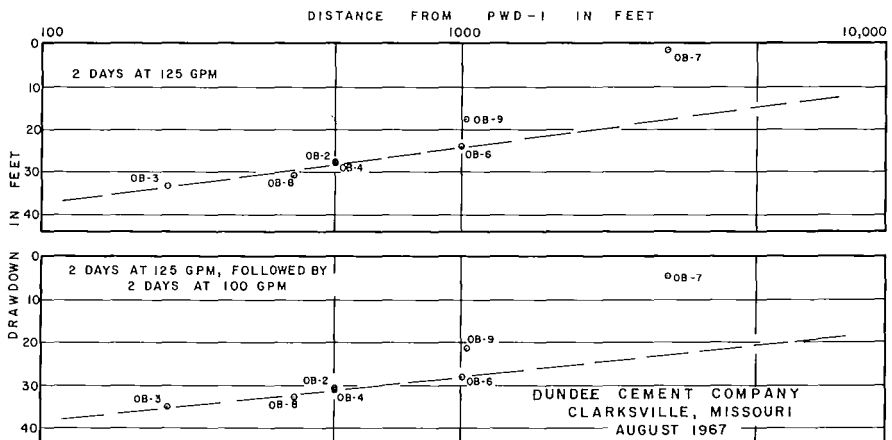


FIGURE 4 — DRAWDOWN-DISTANCE RELATIONSHIPS CAUSED BY PUMPING PWD-1 AT 125 AND 100 GPM

further concluded that, at flood stage of the Mississippi River, the aquifer could transmit no more than about 500,000 gallons per day back to the quarry site, provided there was a clean interface with the aquifer. This relatively small scale field investigation quickly demonstrated that all of the ground-water problems, including that of recharge from the Mississippi River were manageable at very low cost.

This simple example of a highly favorable outcome is not necessarily typical, of course. There are many cases

where large-scale recharge from a surface-water source is an accepted cost of mining or quarrying.

PINE POINT MINES, NWT, CANADA

Pine Point Mines, a subsidiary of Cominco Ltd, operates open-pit mines in an elongate chain of isolated lead-zinc ore bodies along a Devonian dolomite reef in Canada's Northwest Territories. The location, to the south of Great Slave Lake, is indicated on figure 5 and the general array of ore bodies is shown by figure 6. The ore deposits and their geology have been extensively reported by Campbell (4) and Skall (5), among others.

Shortly after initial operations mined off some of the dry ore bodies, Pine Point Mines proceeded in 1968 into what has become one of the largest mine dewatering projects in North America. Total pumpage has been above 40 million gallons per day for years and reached 66 million gallons per day in 1978. The testing programs, the gradual development of the dewatering systems and the practical problems of dewatering in a frigid environment have been reported previously by Calver and Farnsworth (6), by Bra-shears and Slayback (7) and by Vogwill (8), and will be further addressed by K. J. Durston at this symposium.

The primary objective in discussing the dewatering operations at Pine Point is to describe the success this mine has had in handling the transition of a confined or artesian aquifer, in which pumping reduces the pore pressure, to a water-table aquifer, in which gravity drainage of the water in pore storage takes place. The change occurs when pumpage causes the piezometric level to fall below the base of the confining bed and into the strata being pumped. In the author's experience, no other single phenomenon in hydrogeology has caused more problems in the proper evaluation of mine dewatering requirements, or for that matter, in ground-water supply analyses.

The transition involves what hydrogeologists refer to as "delayed yield from storage." The general theory was described by Boulton (9) (10), useful type curves were provided by Prickett (11) and the direct description of artesian to water-table conversion was covered by Moench and Prickett (12). The early application to Pine Point Mines was described by Vogwill (8). Rather than go into a detailed description of the theory, this paper will trace

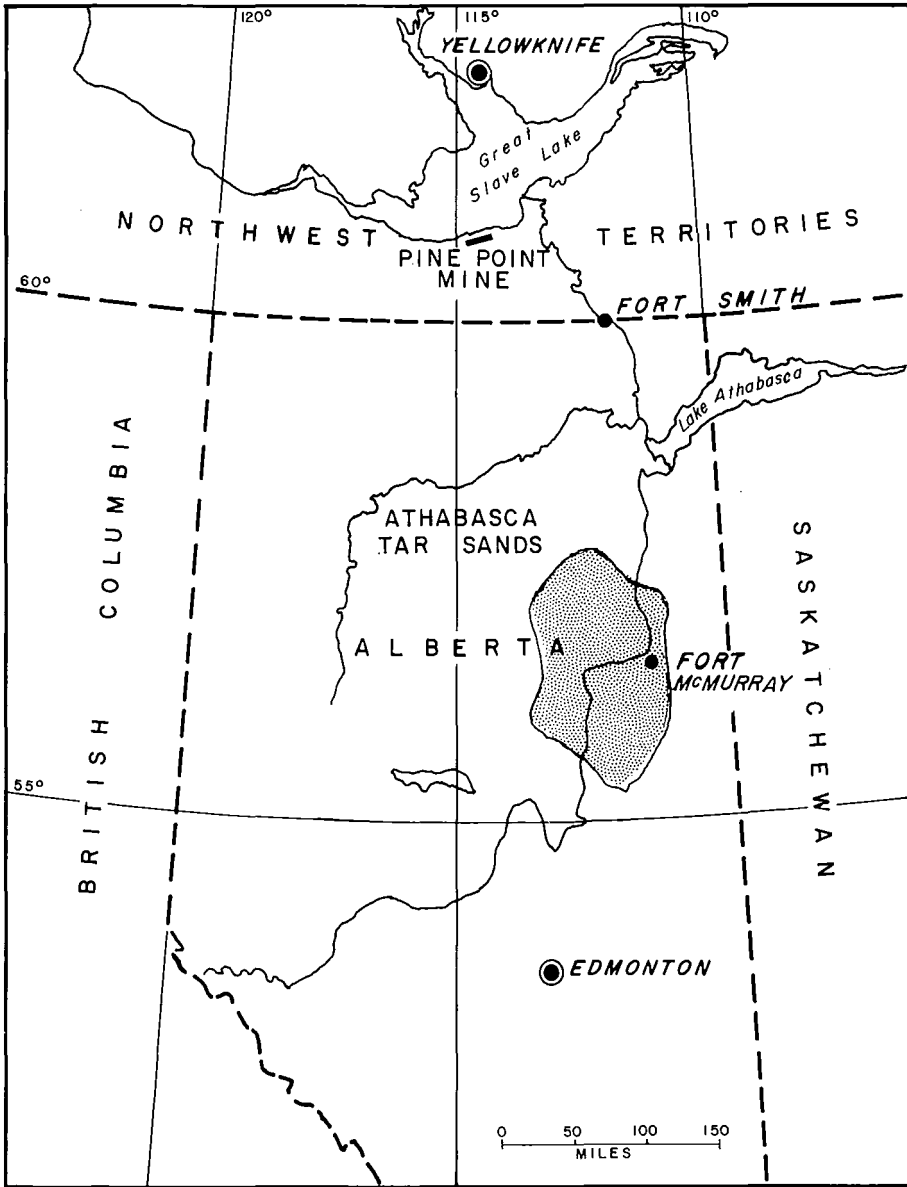


FIGURE 5 - LOCATION OF PINE POINT MINE AND ATHABASCA TAR SAND REGION

the Pine Point experience and illustrate the interpretational problems with a hypothetical drawdown graph.

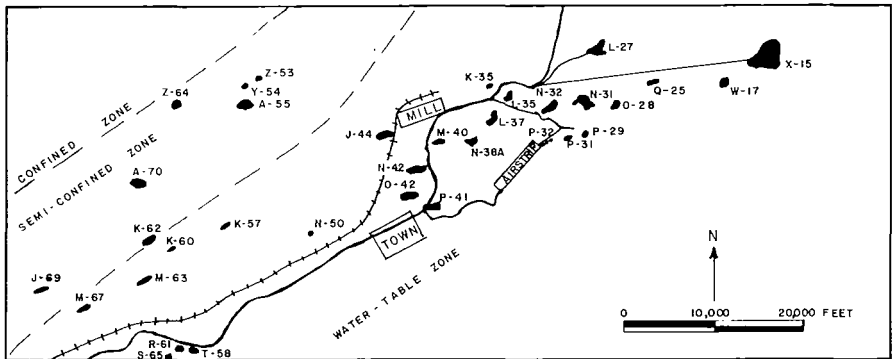


FIGURE 6 — ARRAY OF ORE BODIES AT PINE POINT MINES

The first ore bodies dewatered at Pine Point were in areas with no confining bed and the aquifer response was water-table drainage from the beginning. Figure 7 illustrates a typical family of observation well semi-logarithmic drawdown curves in response to pumping a single well at 1140 US gallons per minute. The curves are typified by an early slow rate of drawdown and the drawdown data gradually fall into a straight-line trend. For this test, the average transmissivity, by log-log and semi-log analysis, was 54,000 gallons per day per foot and the average coefficient of storage was 0.015, or as expressed in water-table terminology, the specific yield was 1.5 percent. These coefficients formed a satisfactory basis for pit dewatering design. The range of aquifer transmissivity at Pine Point is from 35,000 to 90,000 gallons per day per foot. Among the water-table pits, the specific yield ranges from 1.5 to 5 percent (8).

The first ore pit to involve an artesian to water table conversion was designated K-57. When tested, the aquifer coefficients were $T = 41,000$ gallons per day per foot and $S = 0.001$ (8). Note that the storage coefficient was more than a full order of magnitude smaller than the smallest of the water-table cases. The water levels during the K-57 test were not drawn down below the bottom of the confining bed, but in order to mine to full depth, the required drawdown was to levels substantially below the confining bed. As a result of this situation and some operational problems, dewatering of this pit was about 20 feet less than anticipated after one year of pumping (8) and additional pumping capacity was required to meet the mining schedule.

Disregarding the operational problems, what occurred hydrogeologically can be illustrated by figure 8, the

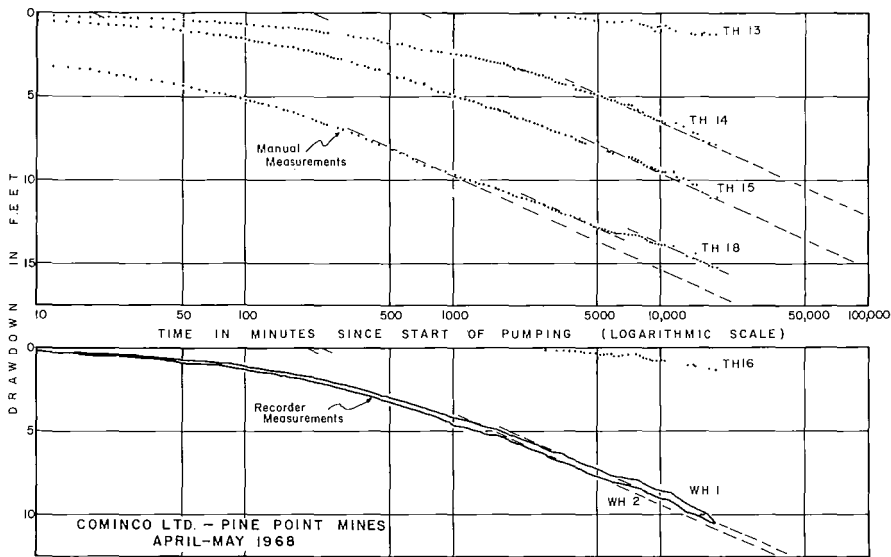


FIGURE 7 - OBSERVATION WELL DRAWDOWN CAUSED BY PUMPING N-42/WH3 AT 1140 US GPM

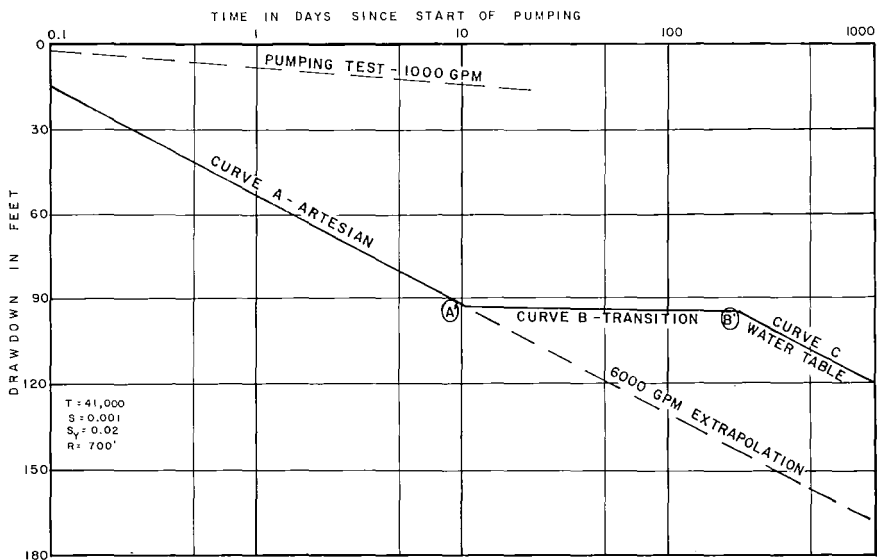


FIGURE 8 - HYPOTHETICAL DRAWDOWN RESPONSE OF PIT-CENTER OBSERVATION WELL, SHOWING ARTESIAN TO WATER TABLE CONVERSION

hypothetical semi-logarithmic drawdown response of an observation well in the central pit area. The upper curve represents the drawdown observed during the pumping test of a single well and Curve A, the extrapolated response to the

pumping of the complete group of pit-rim dewatering wells operating at a combined yield several times the tested pumping rate. At Point A' the actual drawdown response deviates from the extrapolation used for design, which extrapolation worked well for the water-table pits.

Point A' is not clearly defined, but occurs sometime as water levels are drawn below the confining bed. Its actual position at any given observation well is related to the aquifer coefficients, the location and yield of individual pumping wells and the geometry of the aquifer-confining bed interface. Nevertheless, it represents the point at which the extrapolated artesian drawdown trend, controlled by the pumping rate, transmissivity and the small amounts of water released from artesian storage per unit of head change, is interrupted by the transition to water-table gravity drainage of water filling the pore spaces.

Curve B represents the transitional period when parts of the aquifer affected by the cone of depression are changing to gravity drainage response. In the practical sense, it is a time when continued withdrawal of water at a given pumping rate produces very little additional drawdown. This transitional phase is followed at Point B' by Curve C, in which for a thick water-table aquifer, the logarithmic rate of drawdown is equal to that of Curve A.

The critical point, of course, is the delay entailed with Curve B. For the Pine Point case, where the difference between the artesian and water-table storage coefficients is generally somewhat more than one order of magnitude, the approximate delay is a little more than one log cycle of time, which can be insignificant or devastating depending on the circumstances. For the situation shown, if Point A' is reached in 10 days at a given rate of pumping, Point B' where the extrapolated rate of drawdown will resume, will be after about 200 days. Similarly, depending on when Point A' occurs, any drawdown target time would be deferred by about one log cycle of time--1 day to 10 days, 100 days to 1000, 1 year to 10 years, and so forth. Although it has not occurred at Pine Point, it is possible that an artesian aquifer with a storage coefficient of 0.0001 would change over to a water table aquifer with a specific yield of 0.1, a transition involving an effective delay period of 3 log cycles of time--from 10 days to 10,000 or 27 years, for example.

A solution to the problem, as Pine Point Mine personnel

have determined, is to estimate the ultimate water-table specific yield and provide sufficient pumping capacity to drive through the delay barrier early. Fortunately, at Pine Point the water table specific yield of the rock--its effective porosity--is known within a fairly narrow range: 1.5 to 5 percent. Where it has been feasible, the mine has conducted multiple-well pumping tests to pass through the confining bed and observe the water-table behavior of the aquifer. However, for deep pits in the artesian zone, where the confining bed is substantially below the static water level, such tests are impractical and the average specific yield of the rock provides a reasonable basis for initial dewatering design. Such design must, of course, be modified by the results obtained by yield and drawdown monitoring.

In proceeding beyond the Pine Point example, return to figure 8 to consider the implications of a pumping test that is concluded during the Curve B phase. In the absence of hydrogeologic understanding and especially when Curve A is poorly developed, many such tests have been misinterpreted as indicating an exceptionally high aquifer transmissivity or a recharge boundary. Either of these erroneous interpretations lead to projections of a requirement for an excessive number of dewatering wells and an unrealistically large total sustained pumpage. Although such interpretation will not result in the underdesign that is the bane of mine planners and operators, such projections may have a significant detrimental effect on mining feasibility evaluations.

ATHABASCA TAR SANDS, ALBERTA

The Athabasca tar sand deposits in the vicinity of Fort McMurray, Alberta, located on figure 5, contain vast petroleum reserves at least partly within reach of surface mining methods. Two large open-pit mines are in operation, a third is planned and presently in the licensing process, and several more have been investigated for future development. The tar sand ore is found in the Cretaceous McMurray Formation, which unconformably overlies Devonian limestone and shale bedrock (13). The McMurray Formation is comprised of a complex transgressive sequence of salt marsh, fluvial, estuarine and marine deposits of sand, silt and clay (14).

The sands of the main ore zone are impregnated with bitumen--heavy asphaltic petroleum--at grades commonly in excess of 10 percent by weight. Overburden of highly variable thickness includes the Cretaceous Clearwater Formation clays and

sands, Pleistocene tills and stratified drift, and recent deposits including stream alluvium and large areas of muskeg.

The two operating mines and the third proposed by the Alsands Project Group are examples of the extreme diversity of ground-water conditions in the Athabasca tar sand area. Great Canadian Oil Sands Ltd. (G.C.O.S.) has operated an open-pit mine by bucket-wheel excavators since 1967 on the west bank of the Athabasca River, about 25 miles north of Fort McMurray. To date, G.C.O.S. is understood to have had no aquifer problems of significance and operates no formal ground-water control system.

On a property directly abutting the G.C.O.S. lease, Syncrude Canada Ltd. has found very different aquifer conditions. A dragline test pit dug in 1973-1974 encountered significant inflows of water, gas and sand issuing upward from an aquifer in the basal McMurray Formation below the ore body. A dewatering system of 42 wells, having a combined peak yield of almost 350 US gallons per minute, was installed to depressurize these basal water sands beneath the test pit. After about 15 months of pumping, drawdown of as much as 5 feet was discerned $1\frac{1}{4}$ miles from the test pit. Various back-analyses indicated that aquifer transmissivity was on the order of 750 to 1500 gallons per day per foot, and gave local storage coefficients of about 0.00003. However, variable well productivity, inconsistent results at distance, and the presence of significant amounts of dissolved gas gave indications of the heterogeneous aquifer conditions.

For the commercial mine, which went into dragline-excavation operation in the summer of 1977, Syncrude concluded that depressurization of the basal water sands would be necessary, to enhance stability of the mine high walls and to limit the handling problems inherent in wet tar sand. A testing program, involving two patterns of production and observation wells, was carried out in 1974. A typical test pattern array is shown by figure 9. Step drawdown tests and constant-rate pumping tests were carried out to determine aquifer coefficients, boundary conditions and well performance characteristics. Observation well data gave T values ranging from 225 to 3000 gallons per day per foot and S values in the range of 0.0001 to 0.00001.

These tests formed a basis for basic well design and spacing for a system of five rows of pumping wells along the

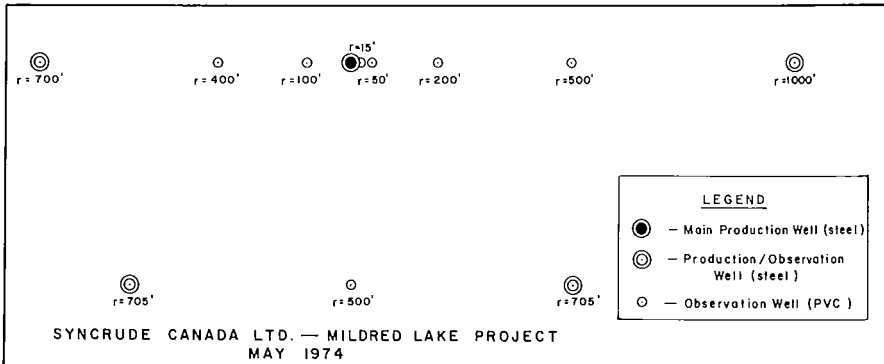


FIGURE 9 — MULTIPLE PRODUCTION WELL AQUIFER TEST PATTERN

14,000-foot long opening cut of the mine. The wells were initially drilled at 200 and 400 feet spacings at an average density of 20 wells per 1000 lineal feet of opening cut. Subsequently, a variety of additional test methods was applied to augment the knowledge of aquifer characteristics, including falling head tests, slug tests, specific capacity tests, laboratory permeameter tests and controlled operational tests. These data indicate a range of field coefficient of permeability from about 0.2 to 300 gallons per day per square foot (14), but values in the range of 10 to 100 gallons per day per square foot were common for the water sands.

Initial storage coefficients were in the range of 0.0001 to 0.00001. However, as depressurization progressed, the evolution of dissolved gas, mainly methane and carbon dioxide, within the aquifer pores, caused substantial changes in the aquifer and well performance. To the hydrogeologist, this appeared to be a reduction in transmissivity and accompanying decrease in well production, and a substantial increase in the coefficient of storage. The reservoir engineers recognized the two-phase behavior as analogous to solution-gas or depletion drive. The transmissivity effect was caused by the rapid decrease in relative permeability to water as the relative permeability to gas increased, and the storage effect was related to highly expansive gas behavior in the pore space. Syncrude has made effective use of an oil-reservoir computer model to predict depressurization progress (14).

Syncrude has drilled about 500 depressurization wells to date and more will follow. Many of the wells already have been removed to make room for mining activities, some never produced significant amounts of water and many have had to be redeveloped to overcome clogging of the well screens

with bitumen. At any given time, 75 to 150 wells may be operating at an average rate of about 5 gallons per minute. In areas underlain by clearly-recognizable water sands, depressurization of as much as 170 feet has been achieved, but in transitional areas underlain by silty sands, tarry water sands or silts, much less drawdown has occurred. No perennial recharge has been observable but leakage of water stored in the basal clay layers has been demonstrated. Continued drilling has shown that large areas of the mine site have little or no basal water sand, but large areas underlain by productive water sands also remain to be mined.

To the northeast of G.C.O.S. and Syncrude, on the east side of the Athabasca River, is the planned Alsands Project Group mine. Drilling exploration, pumping tests, and a 1974-1975 test pit by Shell Canada Ltd. have revealed a basal-zone aquifer substantially different from that at Syncrude. The water sands are generally coarser, cleaner and thicker, and dissolved gas has not been a hydrogeologic factor. Individual wells are known to yield as much as 175 gallons per minute.

An aquifer test in 1972 indicated an average transmissivity of 7000 gallons per day per foot. For an average aquifer thickness of 35 feet, the average field coefficient of permeability was 200 gallons per day per square foot, at a water temperature of 41 degrees Fahrenheit. The storage coefficient averaged 0.0002. Observation well data indicated that barrier boundaries caused the distant depressurization effect to be greater than the aquifer coefficients would indicate, as illustrated by figure 10. The Shell test pit was successfully depressurized by 7 wells, whose combined pumpage was generally less than one million gallons per day, and demonstrated that the Alsands mine is likely to discharge more water than at Syncrude but with far fewer wells.

Elsewhere in the Athabasca area, further hydrogeologic diversity is apparent. One ore body is known to be overlain by more than 100 feet of Pleistocene outwash sands that have yielded as much as 350 gallons per minute to a test well, and have a transmissivity of about 45,000 gallons per day per foot. Unconfirmed reports indicate that glacial outwash aquifers on other leases have yielded as much as 700 gallons per minute on pumping tests. It requires little imagination to suggest that some tar sand leases may have the ore zone sandwiched between a shallow

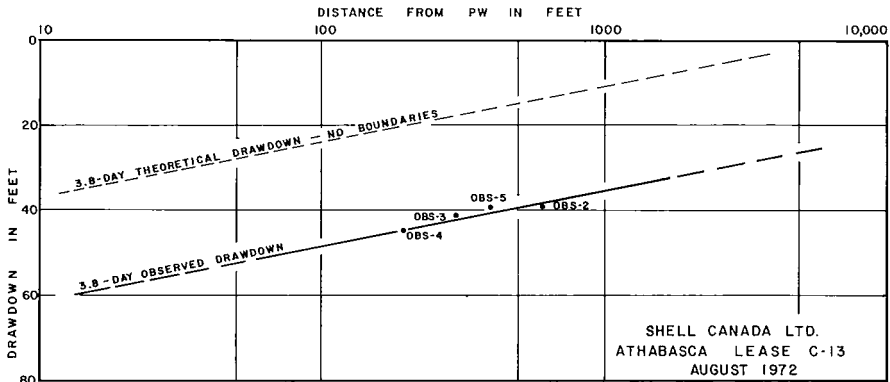


FIGURE 10 - OBSERVED AND COMPUTED DRAWDOWN-DISTANCE RELATIONSHIP CAUSED BY PUMPING WELL AT 175 USGPM, SHOWING IMPACT OF AQUIFER BOUNDARIES

outwash aquifer and deep basal-McMurray Formation water sands--a challenging mine drainage problem.

SUMMARY

These diverse case examples all involved the common thread of field investigations to determine reliable aquifer coefficients, establish aquifer boundary conditions and evaluate aquifer water budgets or sources of recharge. Careful planning and meticulous field work are requisites for any mine dewatering project but even a very large and costly hydrogeologic investigation does not eliminate the risk of unforeseen or anomalous conditions. As with many other aspects of mine development planning, the goal of mine dewatering investigations should be to reduce the probability of drainage risks to acceptable levels.

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