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STUDY OF GYPSUM SOLUTION IN THE WELLAND TUNNEL AREA

by

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Thesis presented to the School of Graduate Studies
in partial fulfillment of the requirements for the
degree of M.A.Sc. in Civil Engineering

UNIVERSITY OF OTTAWA
Canada
1974

ACKNOWLEDGEMENTS

The author is grateful to the St. Lawrence Seaway Authority for making the relevant data available for this study.

The author also wishes to thank Dr. J.S. Scott, Dr. Earl Shannon and, in particular, Dr. J.D. Scott for discussion and guidance in the field of groundwater and hydrochemistry.

PREFACE

Continued solution at an accelerated rate has frequently proved to be a serious cause of problems in engineering structures founded on gypsiferous materials. This situation arises from solution of gypsum leading to the opening up of fissures and ultimate creation of cavities and cavernous conditions. The gradual loss of support to the overlying materials or structures can lead to collapse or subsidence.

This work was carried out to study the long-term solution of gypsum in the Welland area between the Fonthill and Port Colborne drainage divides, and particularly, beneath the Townline Rail/Road Tunnel. The study area is underlain by sedimentary strata of Silurian and Devonian age. Unconsolidated sediments of Pleistocene age overlie the bedrock. The principal aquifer in the region is contained within the upper 10 to 20 feet of the bedrock. The bedrock at the Townline Rail/Road Tunnel site contains gypsum layers, inclusions and veinlets. The design considerations required both temporary and permanent depressurization of the aquifer. The excavation for the tunnel was through 80 feet overburden and the concrete structure was founded on the gypsiferous bedrock.

These considerations raised serious concern, since the increased circulation of the water could accelerate the solution of gypsum leading to the formation of voids or cavities and consequently rapid settlement of the structure. In order to determine the possibility of gypsum solutioning, and to assess the magnitude of the problem, an investigation was

carried out to evaluate the hydrogeological environment and the chemical processes taking place in it. Methods of hydrogeochemistry and principles of chemical thermodynamics were used to determine the degree of aggressiveness of the groundwater towards gypsum. The areas of inactive gypsum solutioning were delineated. The results of this study were incorporated in the design of the tunnel foundation.

A monitoring system was installed to study the influence of dewatering on the boundary between aggressive unsaturated water and saturated water with respect to gypsum.

On the basis of this study, it was concluded that the groundwater at the Townline Road area is saturated with calcium sulphate and the tunnel structure can be founded on the gypsiferous dolomite without any expensive design changes. However the boundary between the saturated and unsaturated water would be monitored until the position of the boundary is stabilized.

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CHAPTER I

INTRODUCTION

1.1 General

Deposits of calcium sulphate either in the form of gypsum or anhydrite are very common in nature. They are recognized to be a cause of serious problems in the field of foundation engineering. The major problems associated with gypsum, such as long-term solutioning, sulphate attack on concrete and deformation characteristics of gypsum, etc., are known to be of considerable geotechnical significance. Continued solution at an accelerated rate has frequently proved to be a serious cause of problems in engineering structures founded on gypsiferous materials. This situation arises from solution of gypsum leading to the opening up of fissures and the ultimate creation of cavities and cavernous conditions. The gradual loss of support to the overlying material or structures can lead to collapse or subsidence. Lack of knowledge of rate, nature and consequence of long-term rock solution can result in a catastrophe, expensive design modifications, costly remedial treatment of foundations, or in some cases abandonment of the site. Such problems have usually taken place as a result of rock solution which was not fully appreciated at the site investigation stage. For this reason, siting of structures on soluble gypsiferous rock has often been avoided and alternative locations developed in better geological conditions.

The site investigation technqiues now exist for the evaluation of cavernous conditions, but there is scarcely any documented case in the literature where the risk of long-term solution of gypsum under the natural as well as altered hydrogeological conditions was fully assessed and monitored. For a safe design it is necessary to determine the rate at which solution may take place relative to the engineering life of the structure.

1.2 Scope of the Thesis

This study describes the method used to study the long-term solution of gypsum in the Welland area between the Fonthill and Port Colborne drainage divides, and particularly, beneath the Townline Rail/Road Tunnel.

The sequence of the development of the problem and of the method by which the problem was solved for design purposes is documented and synthesized as an aid for designers who encounter related problems in the future.

The Townline Rail/Road Tunnel is being constructed on gypsiferous dolomite of the Salina Formation. The upper weathered zone of the bedrock constitutes the major artesian aquifer in that area. The detailed results of the site investigation are outlined and the conclusions for accepting the site as technically suitable are presented. It is suggested that the principles adopted at Townline Rail/Road Tunnel may have a wider applicability, and sites previously considered as unsuitable on the grounds of gypsum being present may, in fact, be quite acceptable.

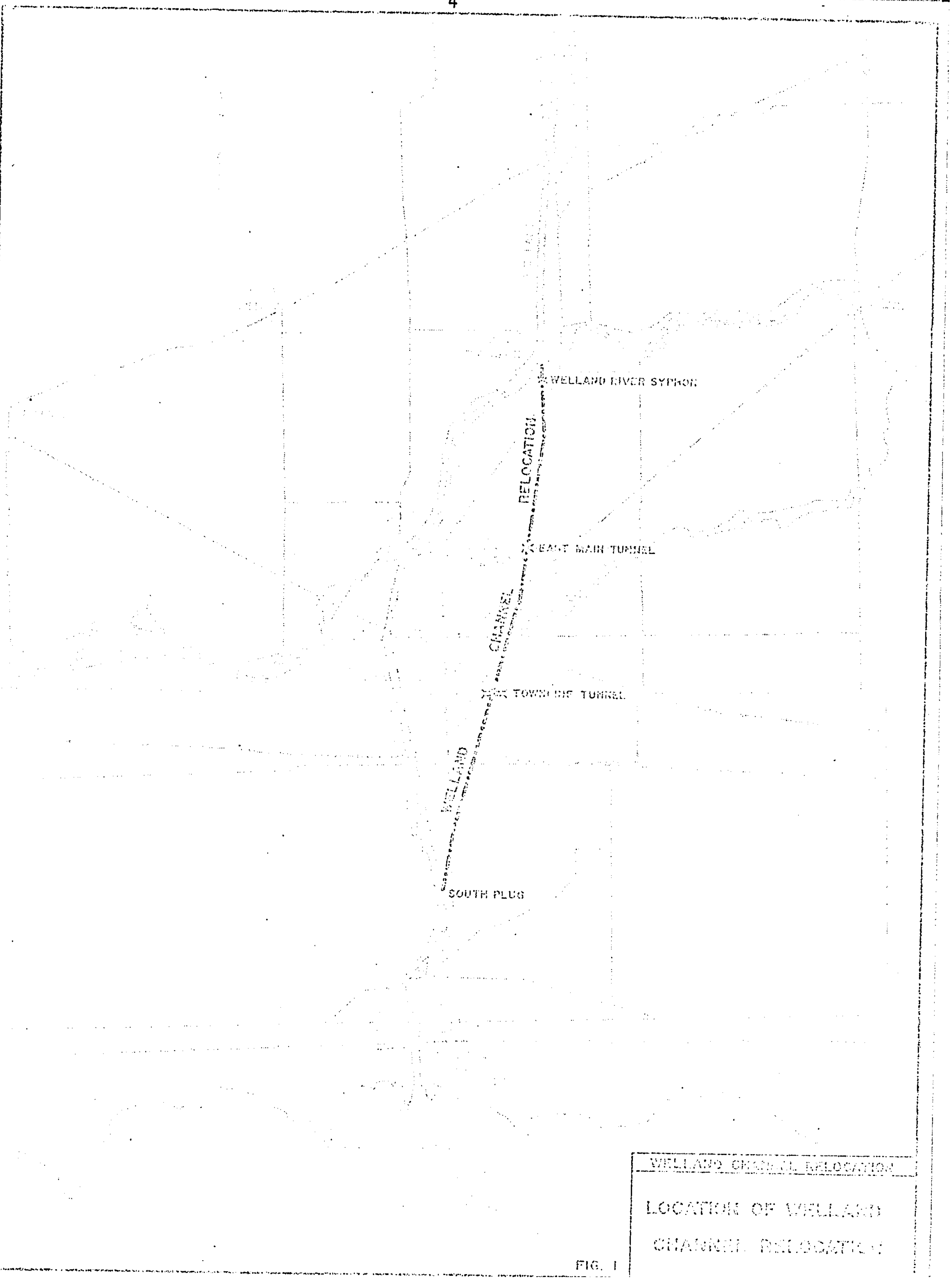
1.3 Location and General Design Considerations

The site of the Townline Rail/Road Tunnel is located in the township of Crowland, where Lyon's Creek crosses Townline Road, at the southeast limit of the city of Welland, Ontario (Figure 1). The topography of this site is generally flat and gently undulating in relief with the ground surface elevation between 570 feet and 580 feet above mean sea level.

The Townline Rail/Road Tunnel designed by Acres Consulting Services has been constructed in an open cut with a maximum depth of approximately 80 feet. The 0.75 percent gradient results in approach cuts which extend over 5 miles in length from grade to grade. The excavation for the tunnel is through overburden consisting of glacio-lacustrine clays and clayey tills. The concrete structure has been founded in gypsiferous bedrock of the Salina Formation. The tunnel structure itself is 1,080 feet long. The piezometric level in the bedrock aquifer was approximately at the ground surface. The principal bedrock aquifer at the tunnel site occurs within the fractured upper 10 to 20 feet of the bedrock. The excavation has created a sink within the artesian aquifer flow system in the bedrock towards which radial flow of groundwater will continuously occur. In order to maintain stability of the slopes and to ensure a dry structure, depressurization of the bedrock aquifer is required both during and following the construction.

1.4 General Description of the Study Area

The Federal Government initiated a major construction project to improve the alignment of the Welland Canal between Port Colborne and Port Robinson which necessitated the construction of vehicular crossings



WELLAND CHANNEL RELOCATION

LOCATION OF WELLAND CHANNEL RELOCATION

FIG. 1

beneath the realigned section of the canal. In the vicinity of the city of Welland two tunnels, Townline Rail/Road Tunnel and East Main Street Roadway Crossing, have been constructed. The East Main Street Roadway Tunnel is sited about 3 miles north of the Townline Tunnel. The East Main Street Tunnel designed by H.Q. Golder & Associates is founded on glacial till overlying the bedrock of the Salina Formation. The construction of the Welland River siphon near Port Robinson has also been completed. Several railway and road bridges required to span the approach cuts on both sides of the tunnel were also constructed. The prevalence of glacio-lacustrine deposits in the Welland area has produced a surface topography characterized by poor drainage and low relief. The central area is a topographic and piezometric "low" bounded to the north and south by areas of higher elevation. The groundwater moves from recharge areas of Port Colborne and Fonthill towards this piezometric low. The Fonthill upland area is underlain by thick deposits of sand and gravel, whereas minor outcrops of bedrock occur near Port Colborne. The Fonthill and Port Colborne water divides to the north and south of Welland City mark the boundary of the area of the present study.

The study area is situated in the physiographic region of the Haldiman clay plane (Chapman & Putman 1951). Main drainage of the area is through the Welland River. Unconsolidated sediments of Pleistocene age comprising till, sand and gravel, and stratified deposits of clay and silt of glacio-lacustrine origin overlie the bedrock. In the central area the thickness of these deposits ranges from 60 to 150 feet.

The study area is underlain by sedimentary strata of Silurian and Devonian age. The bedrock strata that are of interest to this study belong to the Guelph, Saline and Bass Island Formations.

The principal aquifer in the region is contained within the upper 10 to 20 feet of the bedrock and within pervious zones of coarse granular material that occur locally at the overburden/bedrock contact. The piezometric level in the study area ranges from 610 feet in the upland areas to 570 feet near the Welland River, indicating the general direction of groundwater movement.

1.5 Nature of the Problem

Gypsum is known to have far greater solubility than limestone. About 1900 to 2100 mg/l of gypsum can be dissolved in typical non-saline water, as contrasted to only 400 mg/l of limestone ($CaCO_3$). Thus, cracks and cavities can enlarge in a relatively few years if aggressive water remains in contact with gypsum beds. Also, gypsum is a much softer and weaker rock than limestone. Hence, caverns in gypsum are more apt to collapse upon loading by earth embankments or other structures.

During the early stages of the geotechnical investigation, it became evident that the bedrock at the Townline Rail/Road Tunnel site contains gypsum layers, inclusions and veinlets. The water pressure tests also indicated the presence of pervious zones in the bedrock. The design considerations required both temporary and permanent depressurization of the aquifer. These conditions raised serious concern, since the increased circulation of the water could accelerate the removal of gypsum leading to the formation of voids, cavities and consequently rapid settlement of the structure.

It was also anticipated that temporary and permanent dewatering at both construction sites, Townline Rail/Road Tunnel and East Main Street Tunnel, would disturb the groundwater regime. A higher rate of groundwater discharge would lower the piezometric level of the region and establish a steeper gradient which would result in an increase in flow velocity and groundwater circulation. The changes in piezometric surface produced by heavy pumping could also result in reversal of the gradient between the tunnel sites and the Welland Canal and possibly the Welland River. Hence, to evaluate the condition of the foundation rock, the following questions needed to be answered:

(1) - What were the possibilities of encountering solution cavities at the proposed site?

(2) - Were leaching processes active at the tunnel site, and if they were, what was the rate of solutioning as compared to the life of the structure?

(3) - If solutioning was not active under the natural hydrogeological conditions, would it become active when the flow conditions were changed by dewatering? Or, if solutioning was already active would the changed conditions accelerate the rate of solution?

(4) - What long-term trends and changes in the chemical processes would take place and how can such trends or changes be monitored?

1.6 Approach to the Problem

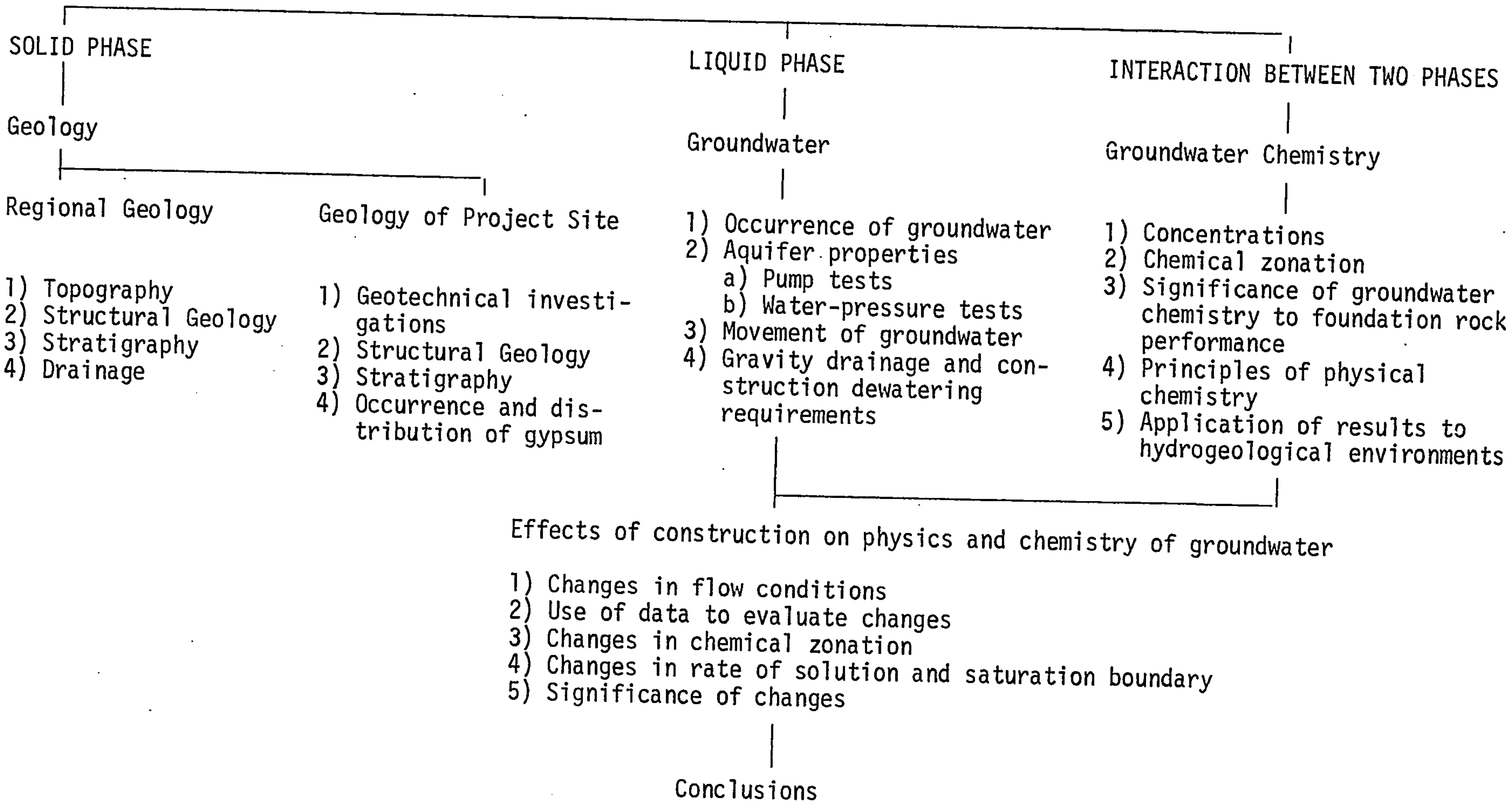
In regions where gypsum-bearing rocks are present, evaluation of the possibility of their leaching by groundwater both under natural and under altered hydrogeological conditions is of importance in foundation engineering. The rate of solution depends on many factors. Some of the most important factors include the lithological character of the parent material, its permeability, its relation to sources and kind of liquid, the rate of circulation of liquid, the time for which the liquid is in contact with the rock, and the volume and the concentration of chemical constitutents in the liquid in contact with the gypsiferous rock. Thus, the knowledge of the hydrogeological environment and the chemical processes taking place in it, is essential to assess the gravity and magnitude of the problem.

The problem is approached by investigating the two important phases, namely, the solid phase and the liquid phase, and interaction between the two, as shown in Diagram A. The solid phase represents the topography and geology of the area, and occurrence and distribution of soluble material. The liquid phase includes the occurrence, movement and chemical character of the groundwater. Leaching of gypsum is a process of the interaction of rock and groundwater. An evaluation of the possibility of its occurrence and scale are being solved by methods of chemical thermodynamics for the gypsum-water system by studying sulphate-calcium equilibrium in the liquid phase. A desirable goal is to know the degree of aggressiveness of the groundwater at many points and to map the distribution of the zones of active solution. The results obtained from the chemical equilibrium study are projected on the map of the study area to determine the approximate position of the boundaries between aggressive unsaturated water and saturated water with respect to gypsum, in order to establish the feasibility of the project and to monitor the future trends. The monitoring wells strategically located near potential mobile boundaries

DIAGRAM A

Introduction

History of Other Structures on Gypsum



SOLID PHASE

Geology

Regional Geology

1) Topography
2) Structural Geology
3) Stratigraphy
4) Drainage

Geology of Project Site

1) Geotechnical investigations
2) Structural Geology
3) Stratigraphy
4) Occurrence and distribution of gypsum

LIQUID PHASE

Groundwater

1) Occurrence of groundwater
2) Aquifer properties
   a) Pump tests
   b) Water-pressure tests
3) Movement of groundwater
4) Gravity drainage and construction dewatering requirements

INTERACTION BETWEEN TWO PHASES

Groundwater Chemistry

1) Concentrations
2) Chemical zonation
3) Significance of groundwater chemistry to foundation rock performance
4) Principles of physical chemistry
5) Application of results to hydrogeological environments

Effects of construction on physics and chemistry of groundwater

1) Changes in flow conditions
2) Use of data to evaluate changes
3) Changes in chemical zonation
4) Changes in rate of solution and saturation boundary
5) Significance of changes

Conclusions

allow an assessment of future trends and changes and serve as forewarning of the approach or spread of aggressive water towards the foundation of the structure.

CHAPTER II

HISTORICAL REVIEW OF STRUCTURES BUILT ON GYPSIFEROUS ROCK

A survey of the available literature revealed that there are several structures built on soluble gypsiferous rock in the United States, U.S.S.R., Italy and France. A history of failure, disaster and other problems is associated with almost all of these structures. Kama hydroelectric station in the U.S.S.R. is probably the only exception. Brief details of some of the structures are as follows:

2.1 St. Frances Dam, U.S.A.

The failure of the St. Frances Dam on May 12, 1928, one week after it was filled is probably the most impressive example of trouble in a foundation containing gypsum (Klein 1962). The foundation of the right abutment consisted of a "conglomerate" which contained gypsum in the form of seams and veinlet fillings. Ransome (1928), after the failure, stated:

> "Chemical analysis made, since the dam failed, of water taken from the Los Angeles aqueduct and from places where seepage water from the reservoir was still flowing from the conglomerate, show a remarkable contrast in soluble constituents. The CaO and SO_4 radicals particularly are many times higher in the seepage water than in the aqueduct

water, showing that active solution of gypsum and other constituents was taking place in the conglomerate."

According to the findings of the American Society of Civil Engineers (Hill, Dennis, Fowler 1929), the dissolving and carrying out of the gypsum produced a condition whereby the rock masses softened by water could have been washed out of the foundation.

2.2 McMillan Reservoir, New Mexico

In Hackberry Draw watershed area, west of Carlsbad, New Mexico, the Seven River gypsum and associated gypseous soils are found. Previous experiences of the Soil Conservation Service (U.S.D.A.) and other agencies show that problems associated with this formation can be very serious (Gunnar Brune 1965).

McMillan Reservoir, north of Carlsbad, was constructed in 1893. By 1909, solution of gypsum caused extensive cracking and subsidence of as much as 40 feet along the east side of the reservoir. An east embankment was constructed to prevent water from reaching the gypsum beds. Despite all efforts leakage became increasingly aggravated. The capacity of the underground channels and solution caverns was estimated to be 50,000 acre-feet and increasing.

Gunnar Brune (1965), report another small dam in this area which failed by differential settlement and piping through highly gypsiferous foundation soils.

2.3 Flood Retarding Structure, Oklahoma, U.S.A.

The Cavalry Creek flood water retarding structure 6, Washita River watershed, a 35 foot high dam, was located 9 miles southeast of Cordell, Oklahoma. In this area massive and thick Cloud Chief gypsum occur. Caverns were encountered on the centreline of the dam. Therefore, the structure was relocated in 1957 farther upstream. The structure was completed in 1957. Shortly thereafter a sinkhole began to form in the right side of the sediment pool and in subsequent years this sinkhole enlarged and four more appeared. The cavern volume beneath the emergency spillway measured about 2,500 cubic yards. The underground channels extended to a depth of 60 feet.

2.4 San Luis Canal and Pumping Plant, California

Klein (1962) has discussed in detail the past experiences in California with hydraulic works in gypsiferous terrains. At the western edge of the San Joaquin Valley, where gypsum rich deposits are prominent, considerable damage and destruction has been done to the canals, roads, transmission lines and buildings, due to land subsidence caused by application of irrigation water to areas underlain by sediments with a small gypsum content. On the southern side of Kern Lake, settlement of the irrigation canal has been so severe that important parts of the facilities had to be abandoned. Referring to the occurrence of gypsum in the foundation rock of Forbay Pumping Plant, San Luis Unit, Klein (1962) states:

> "The approach is cautious in view of our limited experience in California with gypsum and out of respect for the reputa-

tion of this material. Consequently, a basic consideration was to place the structure so that no significant amount of gypsum is beneath any part of the foundation and the appurtenant work."

2.5 American Box Board Company Plant, Grand Rapids, Michigan, U.S.A.

The immediate subsurface material at the site of the American Box Board Company Plant consists of glacial drift of variable thickness. The top bedrock is the Michigan Formation of Mississippian age and consists of dolomite, gypsum and shale. Building settlement was reported first in 1930. In 1933 and 1945 extensive remedial work was done as progressive settlement led to the structural damage. In 1949, there was a failure of the sewer and water main immediately south of the plant at Godfrey Avenue and the Pennsylvania Railroad track. In 1951, a joint study was made by Dr. Ralph B. Peck and Carl A. Bays to determine the cause of settlement. Their investigations led to the conclusion that settlement at the American Box Board Plant is due to solution of gypsum which has been removed by groundwater flowing from the company's power plant water well. The chemical analysis of the groundwater showed that under constant conditions of production the groundwater commonly contained as much as 800 ppm of $CaSO_4$, and that after shutdown, this concentration was increased due to longer contact time between gypsum and water.

2.6 Vabarno Tunnel, Italy and Pomblier Tunnel, France

Redfield (1963) cites the case of the Vabarno Tunnel, driven through anhydrite and gypsum. Completed in 1931, it suddenly began to crack and progressively heave in 1940. A catastrophic failure of the Pomblier Tunnel in St. Felix Avry, in France, due to gypsum solution is mentioned by Oradovskaya (1962).

2.7 Kama Hydroelectric Station, U.S.S.R.

The Kama Hydroelectric Station is built on soluble gypsiferous rock. The study of the changes in hydrodynamics and hydrochemical processes occurring in the foundation of the structure have been carried out on a regular basis since 1959 (Mamenko 1969). During the 14 years of operation, a large amount of hydrogeological and hydrochemical data have been collected, analysis of which provides an assessment of the degree of preservation of the foundation. On the basis of continuous monitoring, the troubles were generally foreseen and small remedial works were performed to prevent the development of any serious problems.

2.8 General Comments

Each of the above mentioned structures was built in typically different hydrogeological environments. However, the interaction of gypsum and water, which adversely affected the stability of the structures, is a common occurrence in all the cases. Since the rate of solution of a mineral depends on the character of the solvent, the rapid solution of gypsum indicated in some of the above cases occurred due to the high degree of aggressiveness of fresh surface water.

The conditions at Townline Rail/Road Tunnel are somewhat similar to the American Box Board Plant case. The chemical characteristics of the impounded body of fresh surface water in contact with the gypsum outcrop are generally constant, hence its degree of aggressiveness does not vary significantly. As contrast to surface water, the chemical characteristics of groundwater vary with the distance it travels through permeable material, therefore the degree of aggressiveness of groundwater varies significantly at each sampling point.

CHAPTER III

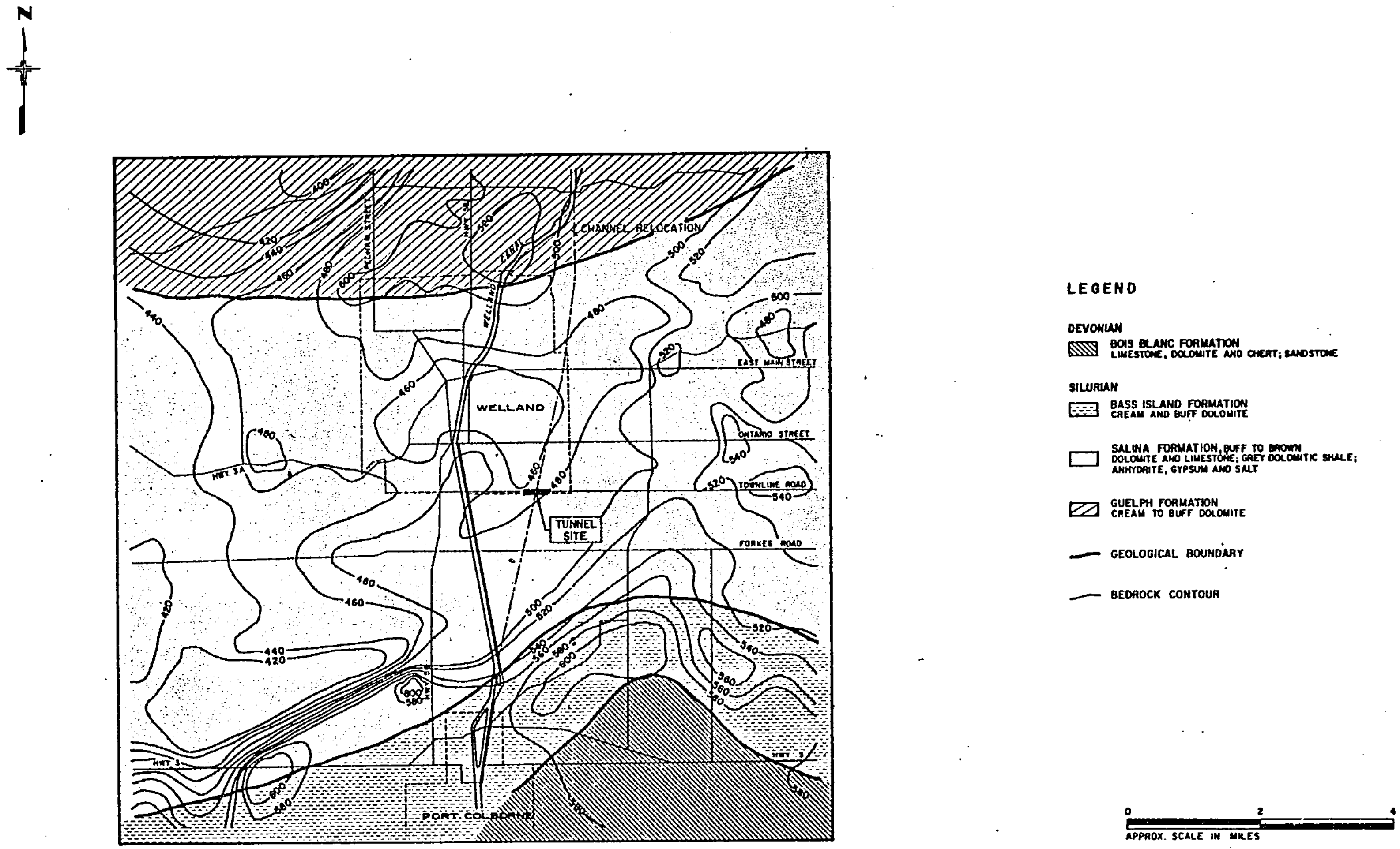
REGIONAL GEOLOGY

3.1 Bedrock Geology

The Niagara Peninsula south of the Niagara escarpment is underlain by Paleozoic sedimentary strata of Silurian and Devonian age. Regionally the strata dip south at an inclination of about 30 feet per mile. The Silurian strata, in the study area, made up of finely crystalline dolomite, dolomite shale, gypsum and anhydrite (Guelph, Salina and Bass Island Formation) are overlain conformably by Devonian limestone and dolomite (Figure 2). The bedrock geology of the Niagara Peninsula has been described in detail by Caley (1940) and Bolton (1957).

3.2 Bedrock Topography

The Onandaga escarpment that trends east-west in the area north of Port Colborne is the dominant feature of the bedrock topography. The bedrock surface, as shown in Fgiure 2, represents the uneven topography that underlies the area prior to glaciation and on which there had developed a drainage system quite different from that of today. Before glaciation the bedrock was subjected to a long period of weathering, erosion and solution. To the south of the escarpment bedrock elevations range from 580 to 610 feet and minor outcrops of upper Silurian strata occur. To the north of the escarpment bedrock elevations range between 400 and 500 feet and the area is characterized by a number of closed depressions. The largest



BEDROCK TOPOGRAPHY AND GEOLOGY

FIG: 2

of these depressions, bounded by the 460-foot contour, underlies the City of Welland.

3.3 Surficial Geology

The surficial deposits of Pleistocene age that cover most of the study area are of glacial, glaciofluvial and glaciolacustrine origin. Glacial deposits consist of unsorted granular till deposited directly by the ice sheet. The lower till immediately overlying the bedrock was probably left by the Wisconsin glacier which may have removed material left by the former glaciers. Deposits of glaciofluvial origin are accumulations of silt and sand which were carried, sorted and deposited by melt water streams. The lacustrine clays and silts were laid down in the several glacial lakes occupying the Lake Erie Basin during the latter stages of the Wisconsin period of glaciation (Deane 1959). The readvancement of the ice over the varved clays deposited the upper till. The thickness of these depsoits ranges from 10 feet, north of Onandaga escarpment to about 200 feet, west of Port Robinson.

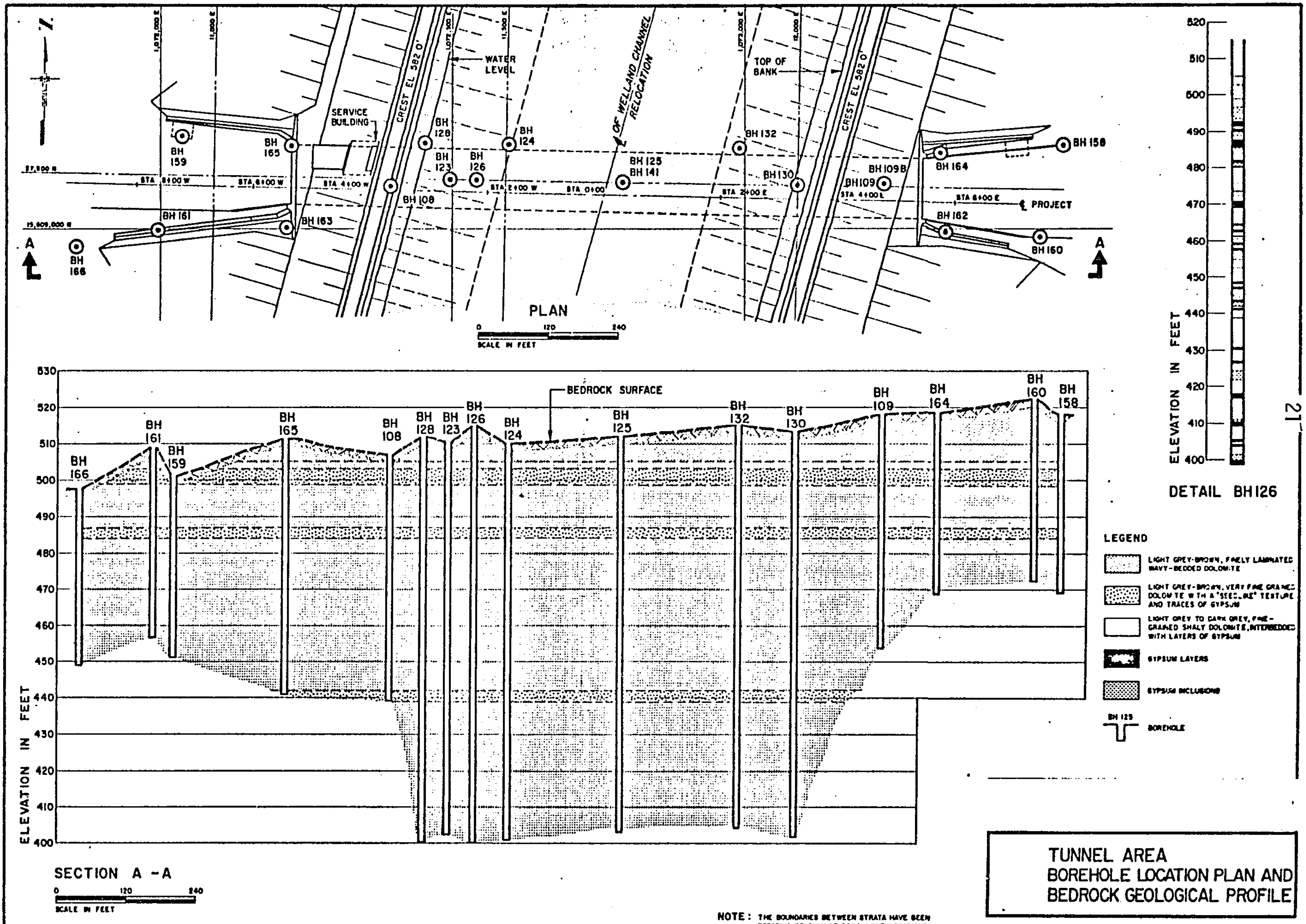
3.4 Surface Topography

The topography north of the Onandaga escarpment is undulating to gently rolling with an average elevation of 580 feet above mean sea level. The study area is bounded in the north and south of the city of Welland by two prominent uplands, Fonthill and Onandaga escarpment. The hill that makes up the drainage divide north of the city of Welland rises to 620 feet in elevation; the escarpment in the south is from 600 to 610 feet above sea level. The area north and south of the Welland River which occupies the central low land is drained by permanent and intermittent creeks.

3.5 Geology of the Project Site - Bedrock

In the project area the bedrock comprises finely crystalline dolomite, argillaceous dolomite and calcareous shale with layers and inclusions of gypsum. These strata occur within the middle part of the Salina Formation of Silurian age. The strata are essentially flat-lying and of uniform thickness.

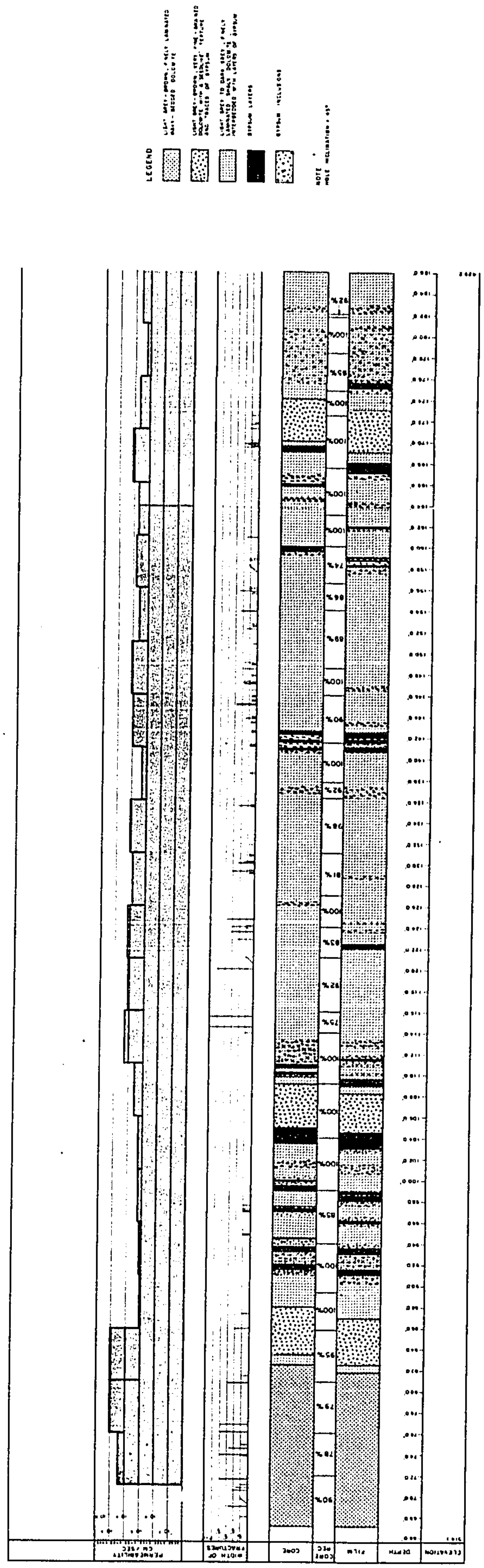
The upper 100 feet of the bedrock at the Townline Tunnel site was investigated by core drilling, water pressure tests and borehole photography. On the basis of the bedrock investigation it has been possible to subdivide the strata at the tunnel site into four lithological units as shown in Figure 3. The grey shaly dolomite beds ranging in thickness from 14 to 40 feet are separated by buff-brown dolomite of 3 to 4 feet thickness, with a seed-like texture produced by elongated gypsum crystals. The elongated gypsum crystals when exposed to fresh water readily dissolve, leaving behind weak honeycomb structure. The lithological change from brown dolomite to grey shaly dolomite occurs through a transition zone of gypsum 2 to 3 feet thick. The average core recovery from exploratory holes generally ranged from 75 to 85 percent. Although no instance of a sudden drop of drill-rod was reported the low core recovery suggested the possibility of voids or weak zones of rock. An additional 5 boreholes, including inclined holes, were drilled and photographed with a borehole camera. Some open joints were observed but no cavities of any significance were identified. A comparison of photolog and corelog is shown in Figure 4.



TUNNEL AREA
BOREHOLE LOCATION PLAN AND
BEDROCK GEOLOGICAL PROFILE

NOTE: THE BOUNDARIES BETWEEN STRATA HAVE BEEN ESTABLISHED ONLY AT DRILL HOLE LOCATIONS. BETWEEN DRILL HOLES BOUNDARIES HAVE BEEN ASSUMED.

FIG: 3



COMPARISON OF PHOTO LOG WITH CORE LOG BOREHOLE 181

FIG: 4

Although no rod drop was observed during the drilling operation, the core recovery was generally low. However, the borehole photography and the 36 inch diameter holes indicated that the bedrock is extremely competent. Since bad drilling or poor equipment can cause blocking of the core in the barrel and consequent grinding of the core, it was believed that the excessive core losses without any indication of rod drop were primarily due to the grinding of gypsum which is a comparatively softer rock.

3.5a Distribution of Gypsum

Throughout the 100 feet of bedrock explored, gypsum is present as layers, lenses, inclusions, nodules and veinlets. Primarily, it is associated with shaly dolomite. Most of the gypsum layers appear as primary deposits within the sedimentary sequence. Some of the joint-fillings, however, appear to be of secondary origin.

The higher concentration of gypsum (i.e., 40 to 45 percent) occurs in the upper 15 feet thick stratum of shaly dolomite between elevation 500 and 485 feet, immediately beneath the tunnel foundation. Gypsum layers range in thickness from 1 to 3 feet, and the thickest layer forms a transition zone between brown dolomite and grey shaly dolomite (Photo 1 and Photo 2). Gypsum generally occurs as a finely crystalline, white and glassy compact mass with a subvitreous lustre.

At deeper zones, slightly impure, pale pink gypsum occurs in lenses and as "marbled" structure with the shaly dolomite between elevation 450 and 470 feet. Small veins of secondary gypsum occur as fibrous to lacy masses within the joints and bedding planes.

After the excavation was completed to the tunnel grade, three holes 36 inches in diameter and 25 to 40 feet deep were drilled in the tunnel area. At least three continuous layers of massive gypsum were identified and the gypsum inclusions appeared to be concentrated in specific zones forming 9 inches to 1 foot thick continuous narrowly spaced bands in the upper stratum of shaly dolomite (Figure 5). No distinct joint system or cavities of significance were observed.

3.6 Unconsolidated Sediments at Tunnel Site

The Pleistocene deposits along the centerline of the tunnel site range in thickness from 60 to 120 feet. These deposits have been subdivided into nine lithological units as shown in Figure 6. Most of these lithological units are lenticular in character and variable in thickness. With the exception of pretill boulders and gravel, in the narrow depression on the western side of the tunnel site, almost everywhere along the centerline of the tunnel and approach cuts, a reddish-brown, relatively impervious clayey till was found at the base of the Pleistocene deposits overlying the bedrock. Thick deposits of silt, sand and gravel, varved clay and massive silty clay overlie the clayey till. The upper till varies in thickness from 17 feet on the eastern side of the tunnel to 22 feet on the western side. The uppermost stratum is a stiff silty clay of glacio-lacustrine origin, occurring over the entire tunnel site area. As it is the surface deposit, it is desiccated, weathered and partly oxidized and contains traces of organic material.

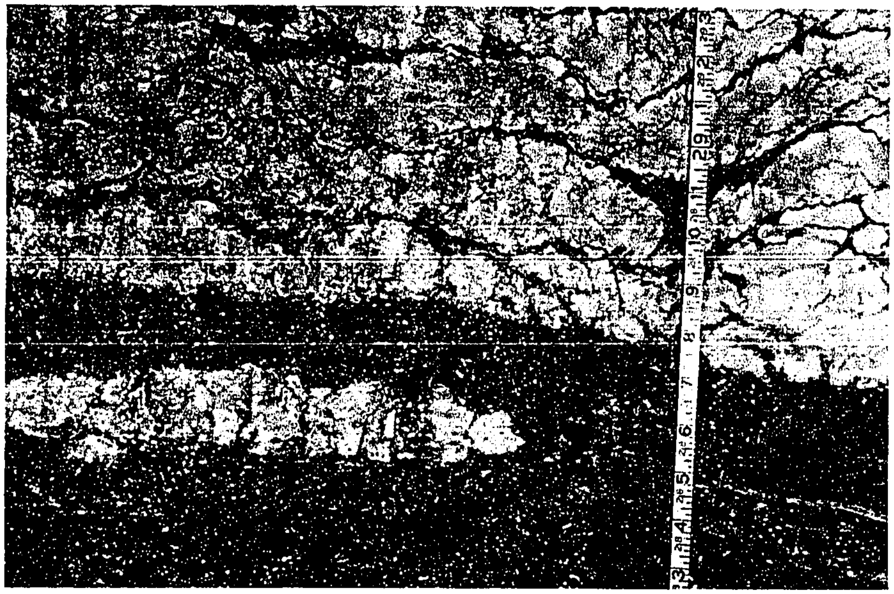


Photo 1

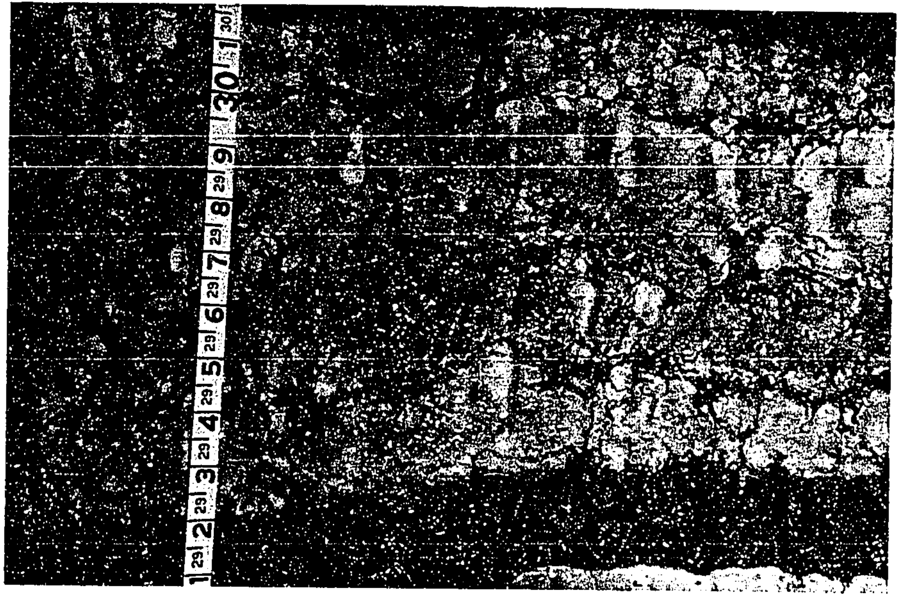


Photo 2

WELLAND CHANNEL RELOCATION

GYPSUM LAYERS

IN 36" DIA. HOLES

FIG - 5

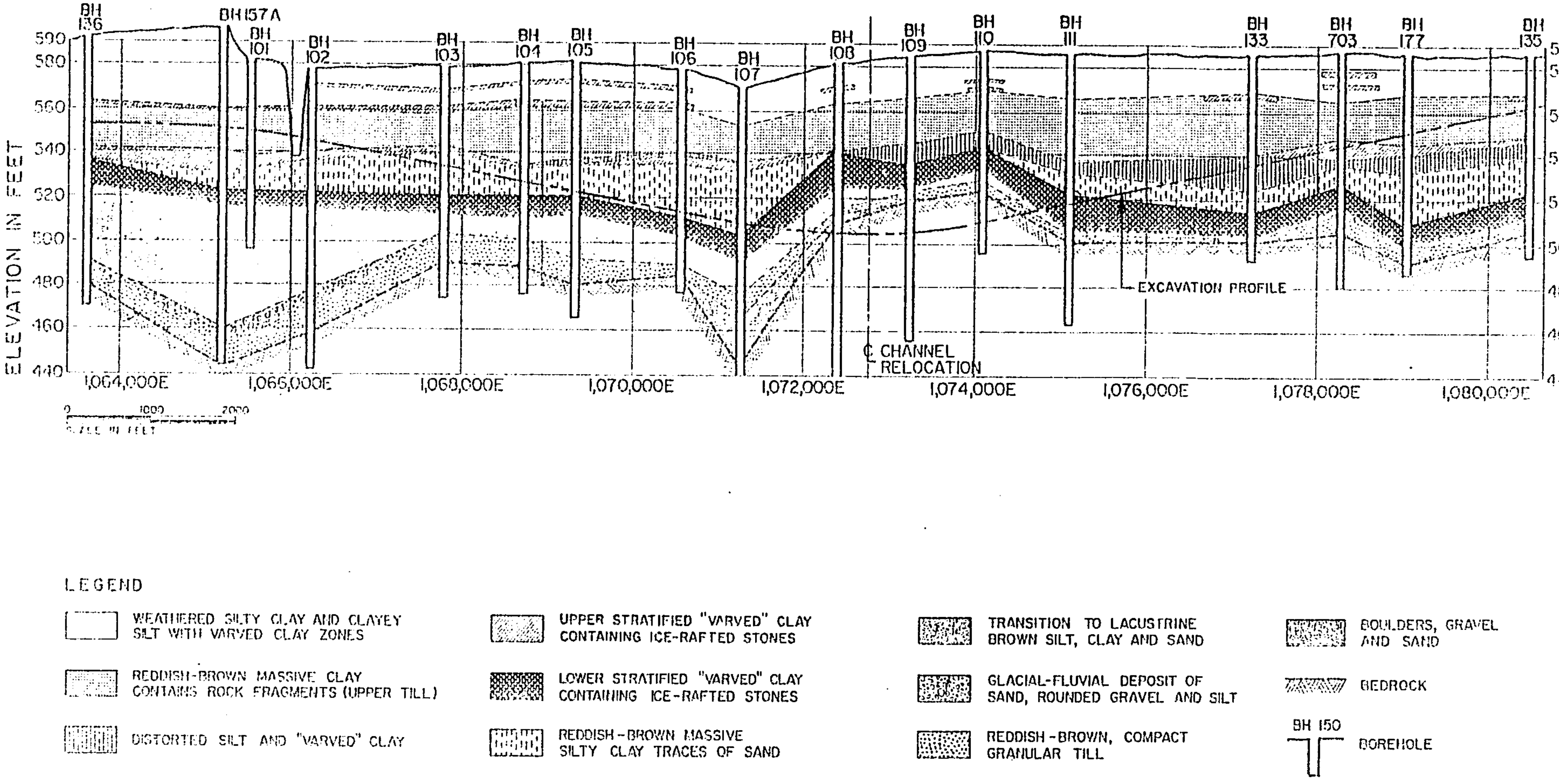


FIG-6 PROFILE OF THE OVERBURDEN ALONG THE CENTRELINE OF THE TUNNEL AND THE APPROACH CUTS

CHAPTER IV

HYDROGEOLOGY

4.1 Occurrence of Groundwater

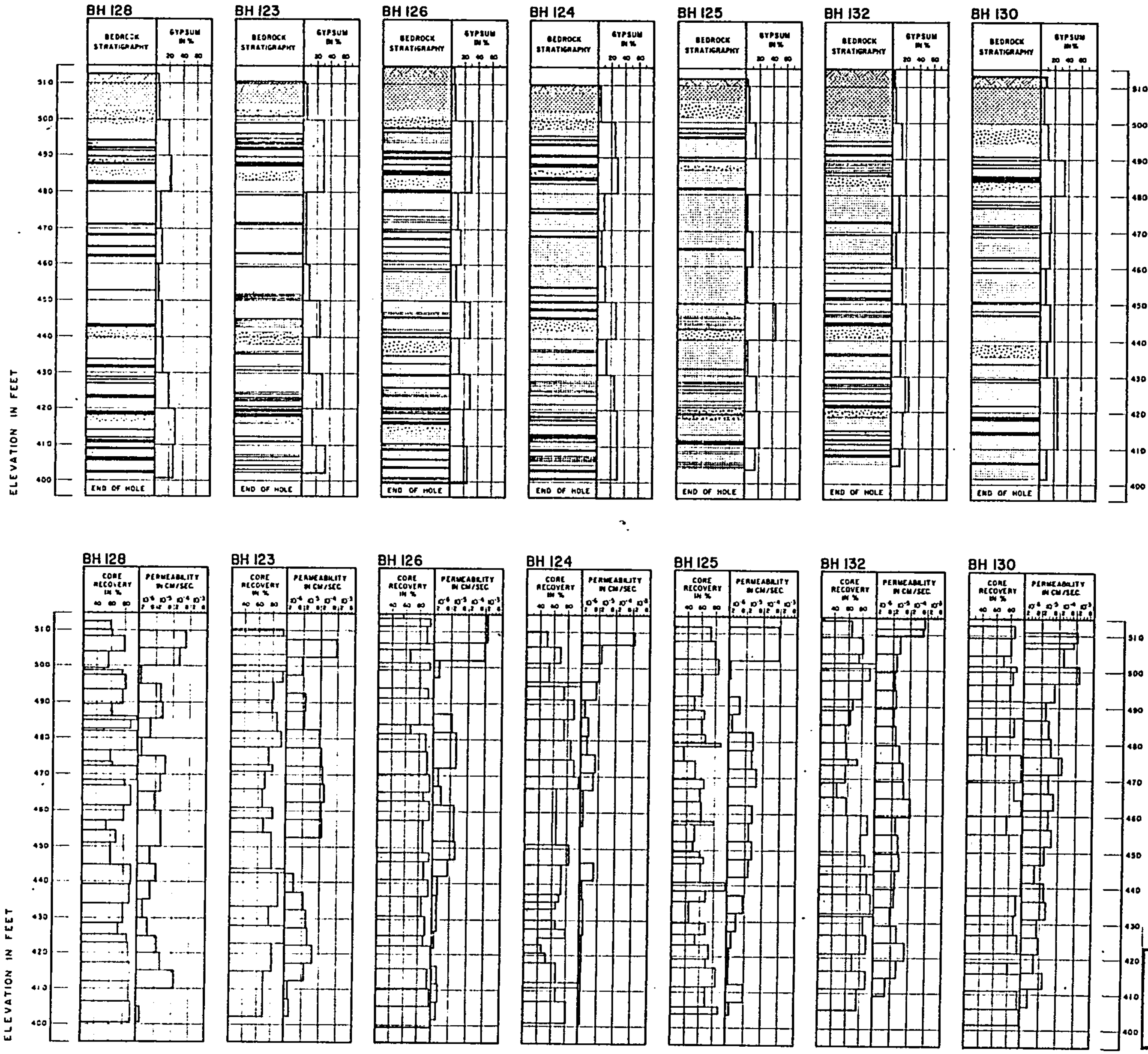
The principal source of water supply in the Welland region is the Silurian bedrock aquifer. The thickness of the water-bearing zone varies from 5 to 20 feet. The aquifer is overlain by relatively impervious lacustrine sediments of varying thickness, which form an effective confining layer. Thus, the aquifer is under confined artesian conditions and the movement of groundwater through the rock mass is controlled by fracture permeability. Locally, sand and gravel lenses within the drift also serve as a source of water supply for the rural population. The main water-bearing zone at the tunnel location is contained within the upper 10 to 15 feet of the weathered and fractured dolomite of the Salina Formation. Unconsolidated deposits of till and lacustrine sediments that overlie the bedrock are practically impervious except for local pervious zones at the bedrock overburden contact. The bedrock formation below the main aquifer consists of discontinuous zones of low permeability surrounded by essentially impermeable rock. A highly mineralized NaCl type brine occurs at deeper zones.

4.2 Properties of Bedrock Aquifer

A number of pumping tests were run to determine the quantitative properties of the aquifer near the Welland River syphon, East Main

Street, Townline Road and Ramey's Bend. The values of transmissibility varied from 2,000 gpd/foot at the syphon site to 90,000 gpd per foot near Townline Road (Farvolden and Nunan 1970). The movement of groundwater in the aquifer is predominantly through secondary openings. Joints solution channels and bedding fractures account for most of the aquifer permeability. Because of the heterogeneity of the secondary openings, pumping tests gave a variable result over a wide range. The hydrogeologic properties of the bedrock at the tunnel site were assessed by means of full-scale pumping tests with the use of multiple observation wells in January 1968, by Acres Consulting Services. The values of transmissibility calculated from aquifer performance tests ranged from 2,000 gpd/foot to 53,000 gpd/foot. The average value of the transmissibility 23,000 gpd/foot, however, more truly describes the water transmitting ability of the formation as a whole. The permeability of the bedrock at the tunnel site was also examined by packer tests carried out in NX boreholes over 10-foot stages soon after drilling. The results of these tests demonstrated a noticeable decrease in permeability with depth (Figure 7). As would be anticipated, the coefficient of permeability values in the upper part of the bedrock were of the order of 10^{-3} to 10^{-4} cm per second and in deeper zones 10^{-4} to 10^{-6} per second.

The reliability of the water pressure tests depends on the quality of the equipment and the experience of the inspector. If the equipment is poor or the observer is inexperienced, the blocking of lines, leakage of packers or a faulty pressure gauge can give extremely erroneous results. It is observed that generally the low permeability values are more reliable than the high values.



LEGEND

- ▨ LIGHT GREY-BROWN, FINELY LAMINATED WAVY-BEDDED DOLOMITE
- ▒ LIGHT GREY-BROWN, VERY FINE-GRAINED DOLOMITE WITH A "SEEDLIKE" TEXTURE AND TRACES OF GYPSUM
- ☐ LIGHT GREY TO DARK GREY, FINELY LAMINATED SHALY DOLOMITE, INTERBEDDED WITH LAYERS OF GYPSUM
- ■ GYPSUM LAYERS & INCLUSIONS
- ▧ BEDROCK SURFACE

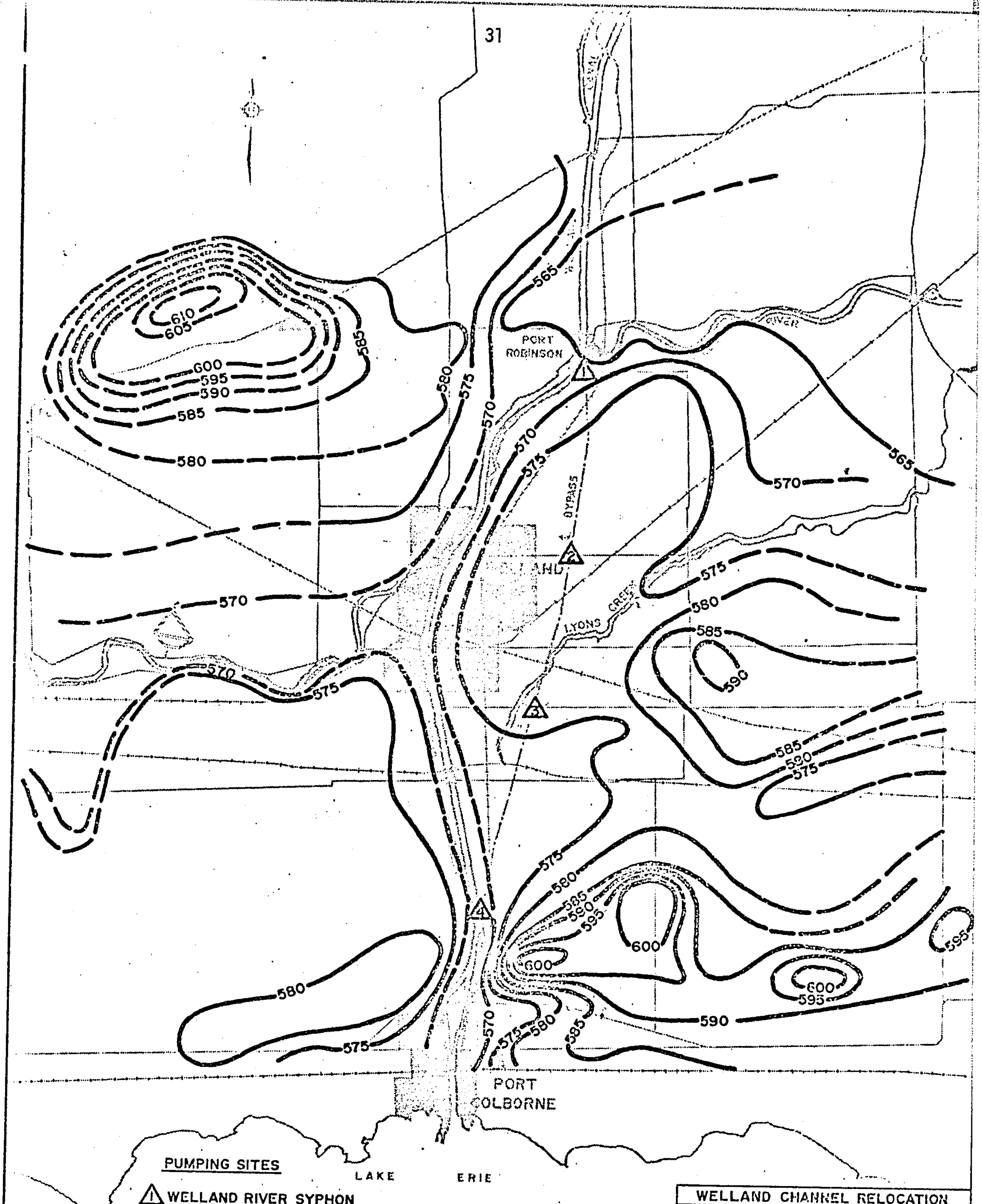
TUNNEL AREA
BEDROCK STRATIGRAPHY,
PERMEABILITY AND
CORE RECOVERY

4.3 Piezometric Surface Map

In order to determine the direction of groundwater movement and the locations of recharge and discharge areas, a piezometric surface map of the bedrock aquifer was compiled (Figure 8). The map was constructed with a 10-foot contour interval from water well data collected from water well records published by the Ontario Water Resources Commission and from piezometric data obtained from the St. Lawrence Seaway Authority and Department of Highways, Ontario. To attain sufficient areal coverage of wells, within the Township of Crowland, Thorold, Pelhem and Wainfleet, information covering the period 1955-1967 was used. Thus, the piezometric surface map obtained is a composite surface representing the average water level conditions for the period of record. Although the initial piezometric configuration may have varied from that interpreted from water well data, it is believed that the interpretation presented is sufficiently accurate for the purpose of determining directions of regional groundwater flow during the preconstruction period.

4.5 Groundwater Movement

The groundwater flow pattern is controlled primarily by the distribution of piezometric head, which is a function of the topography within the limits of the flow system and of the variations in the permeability of the materials through which the water moves. The pattern of groundwater flow involves movement of water from uplands into valley floors or the bottom of the rivers, associated with progressive loss in potential (See Appendix II). The flow pattern in the study area is controlled largely by two piezometric highs shown in Figure 8. The piezo-



PUMPING SITES

- 1 WELLAND RIVER SYPHON
- 2 E. MAIN ST. TUNNEL
- 3 TOWNLINE RD. TUNNEL
- 4 SOUTH PLUG

SCALE

0 1 2 MILES

FIG-8

WELLAND CHANNEL RELOCATION

PIEZOMETRIC CONTOURS
PRIOR TO INTERFERENCE
(INFERRED)

BY HYDROLOGY CONSULTANTS LTD.

metric map of the bedrock aquifer indicates the 600-foot piezometric contour is closed near Port Colborne and Fonthill, and these "piezometric highs" are interpreted as indication of recharge. As a consequence of congruence of topography and piezometric surface, the underground water divide can be considered to coincide with the surface water divide (Schicht and Walton 1961). Hence, recharge is derived entirely by precipitation and probably occurs over the entire upland areas. The upper 5 to 20 feet of bedrock is, in effect, an aquifer with essentially horizontal flow that is being recharged from above. The direction of groundwater movement as determined from isopiestic lines indicates a possible discharge occurring in the vicinity of the Welland River, and at places near the Welland Canal. With a permeable layer at some depth below the river, a longitudinal component of flow in the direction of river flow may exist in this permeable layer (Meyboom, Van Everdingen and Freeze 1966).

The highly mineralized water at depth generally results from the poor circulation of water, which in turn is caused by inadequate discharge of the deeper water. The presence of salty water below the fresh water aquifer places limitation on the amount of fresh water that can be withdrawn without causing serious contamination. No information was available to determine the possibility of upward flow from deeper zones in the bedrock during the preconstruction period. However, under natural conditions, the water table in the overburden and the piezometric surface for the aquifer at the tunnel site were identical.

CHAPTER V

HYDROCHEMISTRY

To understand fully the hydrogeologic environment and to assess the possibility of the solution of gypsum, it is important to study in detail the chemical character of the solvent which comes into contact with the soluble mineral. The knowledge of the variations in the total concentration, individual ions concentration, progressive changes in chemical type of water and the extent of area occupied by each type, is essential to minimize the possibility of erroneous interpretation and to analyze the future changes in chemical composition of groundwater which may take place due to alterations in the flow conditions. The direction of groundwater movement and the locations of recharge and discharge areas as interpreted from the piezometric map can also be confirmed by studying the changes in total dissolved solids and water type, based on the dominant ions in solution.

However, the first problem was to find an economical approach in selecting water samples for complete chemical analyses so that the minimum number of water samples provided the maximum information regarding the changes in chemical composition of the groundwater over the whole region. The problem was resolved by limiting the study area between the natural water divides and by using the conductivity values as guidelines to select sampling locations.

5.1 Specific Conductance

A preliminary assessment of the groundwater chemistry was made by obtaining numerous specific conductance measurements which provided a suitable basis for obtaining water samples for complete chemical analysis. The conductivity contours shown in Figure 9 were prepared from the values determined with a portable field solubridge. The measurements also helped in interpolating the contours of total dissolved solids and individual ion concentration. The relationship between specific conductance and total dissolved solids is illustrated in Figure 10. An approximate value of the total dissolved solids may be obtained by multiplying the corresponding conductivity values by a factor of 0.8. This relationship is based on the data obtained from the Welland area.

5.2 Sampling and Chemical Analyses

The first study of the chemistry of the groundwater is based on the results of the analyses of 43 selected samples of water. The locations from which the samples were taken are shown in Figure 11. Most of the samples were collected from piezometers and farm wells and a few from pumping wells during the aquifer tests. The piezometers were generally flushed and pumped with compressed air before collecting the representative samples. The samples from farm wells were obtained after running the wells for a short period of time. All samples represent the water from the major bedrock aquifer. During the same period (July 1968) Department of Highways reported some partial analysis of water samples from overburden and bedrock in the vicinity of the East Main Street Tunnel.

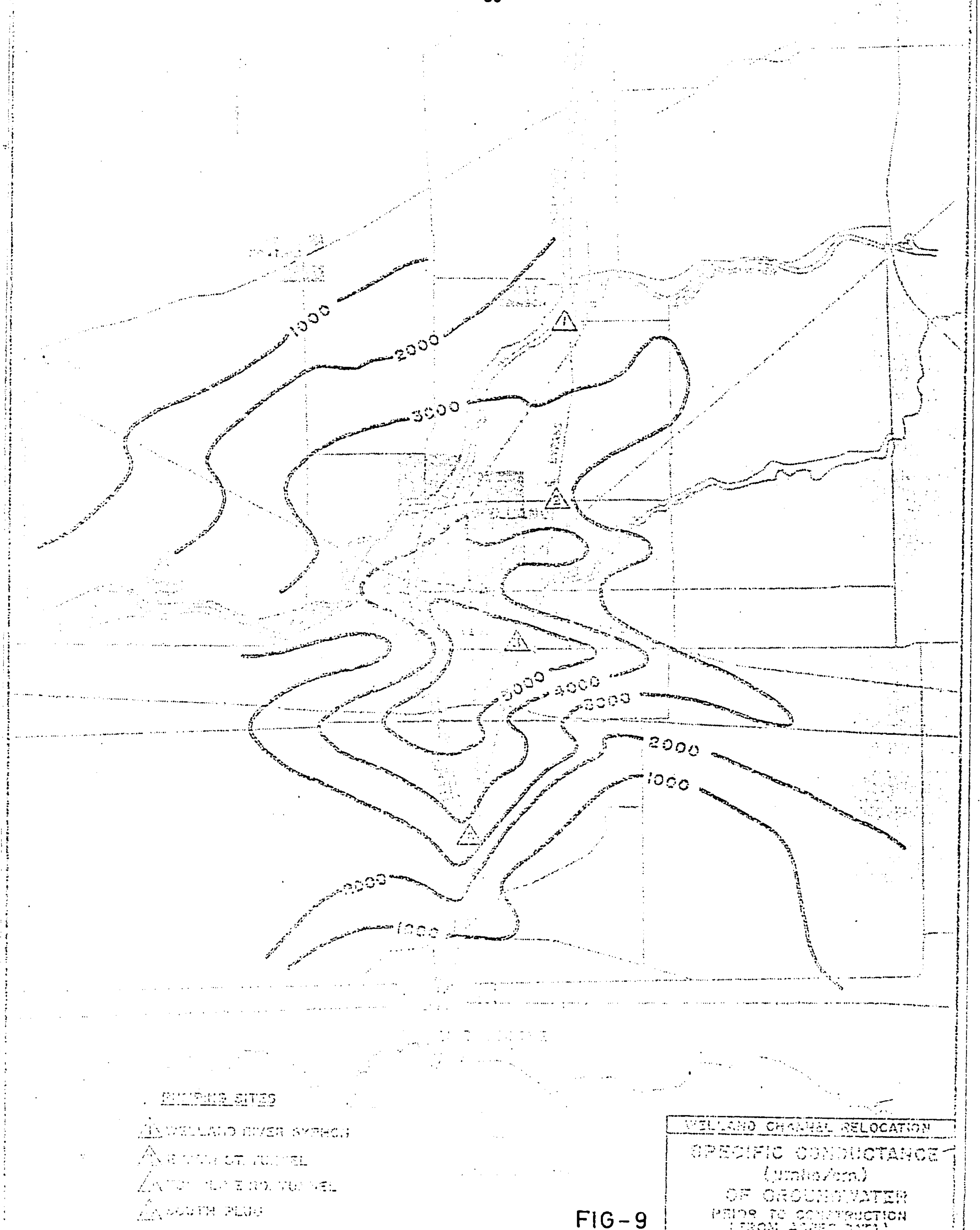
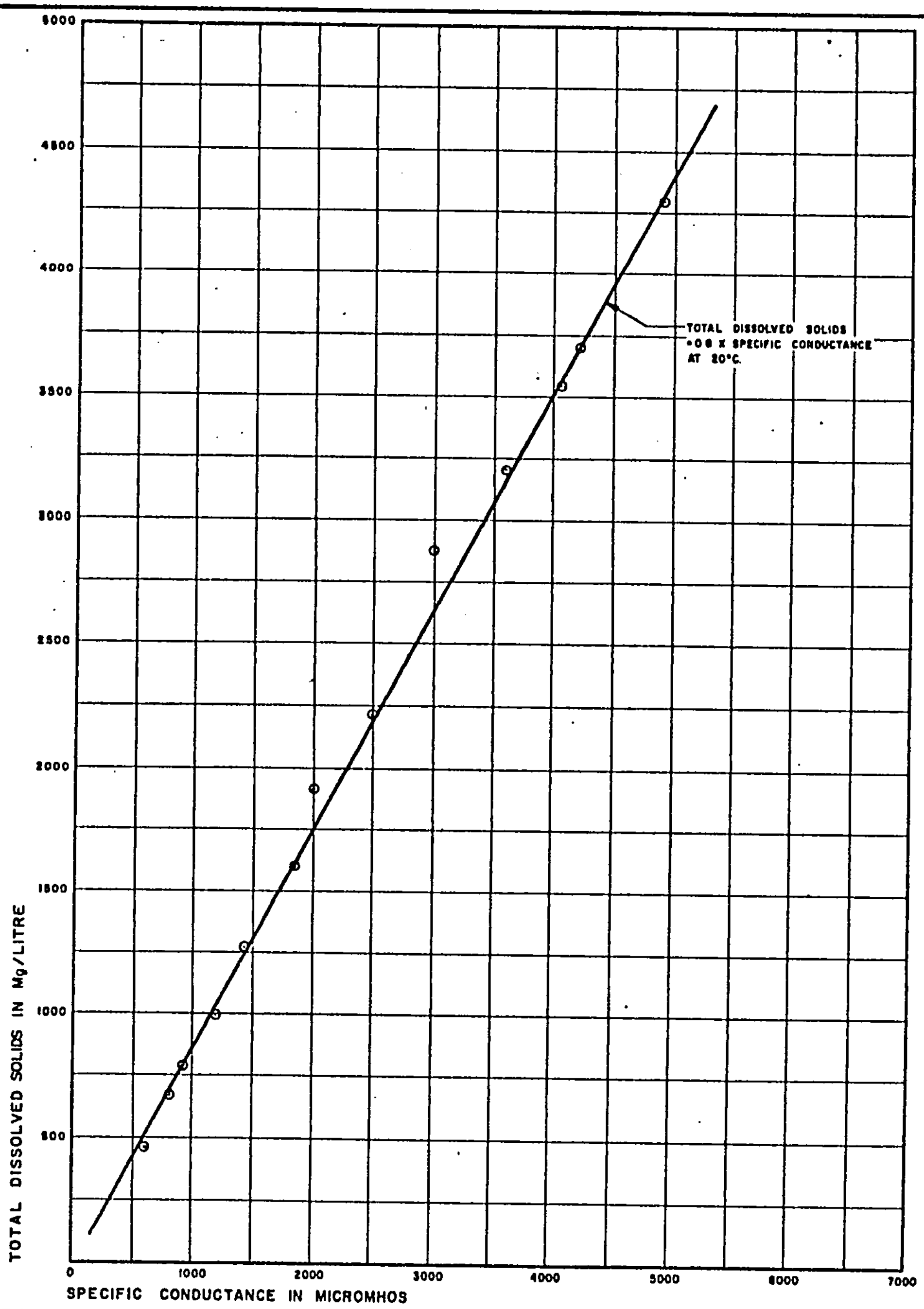


FIG-9

WELLAND CHANNEL RELOCATION

SPECIFIC CONDUCTANCE
(µmho/cm)
OF GROUNDWATER
PRIOR TO CONSTRUCTION
(FROM ASPEC DATA)



RELATION OF GROUNDWATER CONDUCTANCE TO TOTAL DISSOLVED SOLIDS

FIG: 10

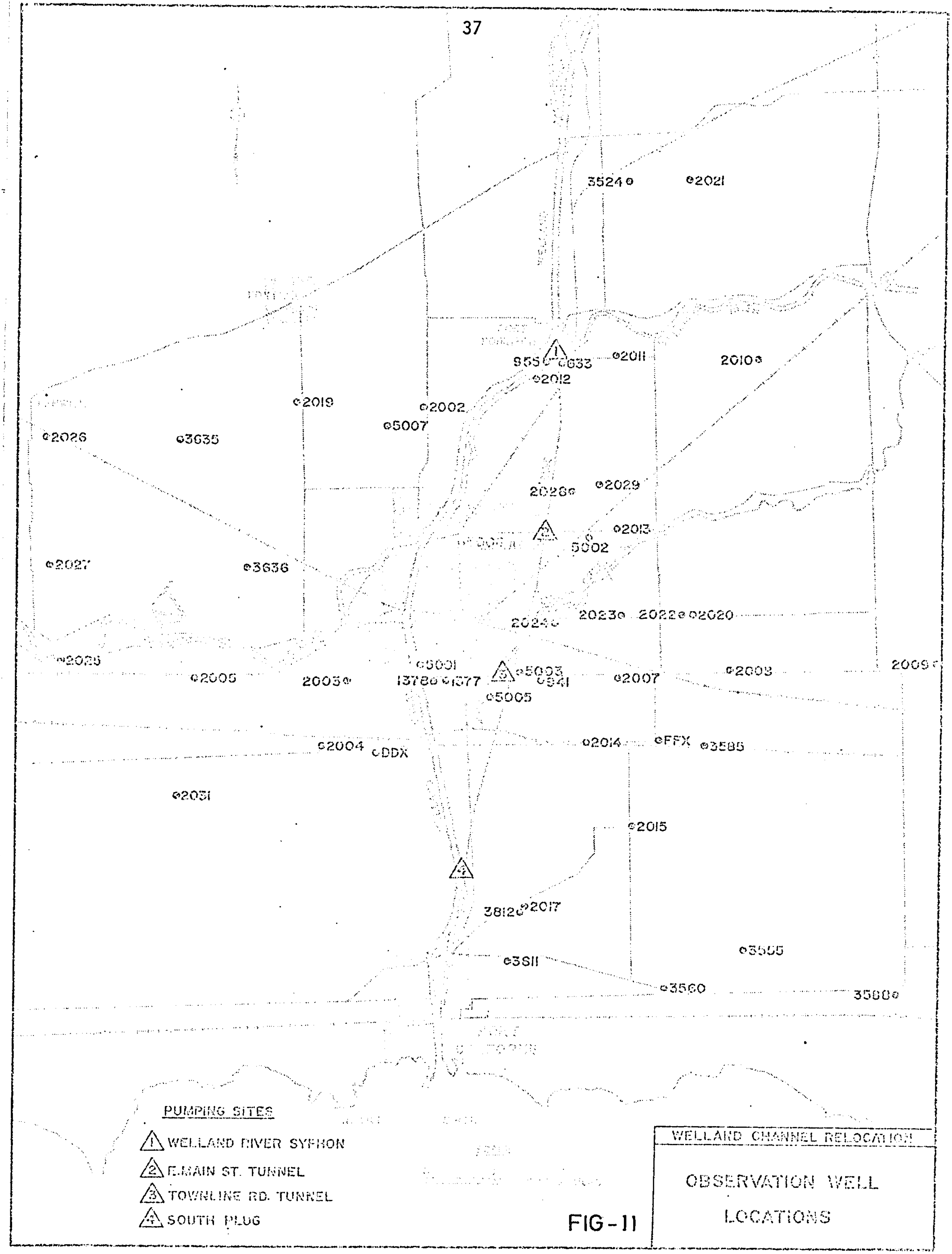


FIG - 11

WELLAND CHANNEL RELOCATION

OBSERVATION WELL LOCATIONS

To study the effect of construction dewatering, 43 water samples were collected in February 1970. Three water samples from 100 feet in the bedrock were also obtained for analysis. The results of the chemical analysis are given in Table 1. The samples were collected by Acres Consulting Services and the St. Lawrence Seaway Authority. The analyses have been carried out in the laboratories of the Calgon Corporation Limited, Ontario Water Resources Commission and the Inland Waters Branch. In most of the analyses Na and K were determined by the method of differences.

5.3 Variations in Total Concentration

The amount of material dissolved from the rock depends chiefly on the amount of water in circulation, the concentration and composition of the material already dissolved in the water, the chemical composition of the water, the nature of openings, the distance water moves and its rate of movement. Within the study area the mineralization of groundwater varied from 320 mg/l in the recharge areas to 11,000 mg/l around the tunnel site. The lines of equal concentration of dissolved solids agree closely with the pattern of groundwater movement as interpreted from the piezometric map. A progressive increase in total dissolved solids away from the upland areas of Port Colborne and Fonthill towards Welland City is clearly demonstrated by Figure 12. The areas low in total dissolved solids, i.e., less than 1,000 mg/l, are underlain by dolomite of Bass Island and Guelph Formations, and the area with high total dissolved solids by the Salina Formation.

TABLE 1

Preconstruction Water Analysis

Date of Sampling: July 20, 1968
Data of Analysis:

Source: H. G. Acres Limited
By: Calgon Corporation

Well No.	No.	T.D.S.	Ca (ppm)	Mg (ppm)	Na (ppm)	SO_4 (ppm)	cl (ppm)	HCO_3 (ppm)
N	1	443	69	24	24	250	3	73
48	2	535	105	22	194	80	330	289
MM	3	662	137	16	23	250	8	228
41	4	754	70	73	46	300	41	234
CC-2	5	977	226	37	4.1	550	34	126
00	6	1,578	277	94	60	1,000	98	49
40	7	1,322	257	52	60	800	25	118
LL	8	1,932	398	104	7	1,200	2	221
A	9	2,246	548	30	1	1,550	8	110
EE	10	2,893	562	183	1	1,650	22	476
M	11	2,785	521	204	1	2,000	23	37
G	12	3,192	541	154	300	1,950	198	49
BH-108	13	10,574	1,144	345	2,200	1,600	5,200	85
BH-161	14	9,346	1,026	292	1,681	2,150	3,900	97.6
BH-167	15	9,243	1,200	323	1,603	2,150	3,850	117
W-963	16	178	23.2	6.2	23	35	6	53
W-982	17	402	55.	17.	0.5	100	33	163

Table 1 - Preconstruction

- 2

Date: 1966 and 1967

S.L.S.W. by: Department of Energy
Mines and Resources

Well No.	T.D.S.	No.	Ca	Mg	Na	SO_4	cl	HCO_3
W-628	3,041	25	504	143	228	2,030	34	129
-689	2,507	26	495	118	86.9	1,684	62	89.1
-887	2,632	27	543	117	98	1,675	138	84.2
Flowing well	2,808	28	505	166	115	1,843	101	115
-951	2,476	29	475	125	93.8	1,665	61	64.7
-6	2,510	30	504	111	88	1,727	21	82.1
-9	2,846	31	488	146	148	2,000	16	59.9
-11	2,463	32	523	102	70.5	1,664	10	155
-12	2,795	33	481	152	115	2,002	17	54
-48	2,708	34	529	128	99	1,794	92	83
-49	2,755	35	505	127	136	1,880	57	66
-50	3,380	36	555	161	265	1,945	370	116
-51	2,660	37	516	139	92	1,800	15	155
-53	3,990	38	488	146	118	1,784	100	46.4
-54	2,786	39	500	148	137	1,730	185	137.0
.Well 5	2,498	40	500	112	91	1,657	74	80.6

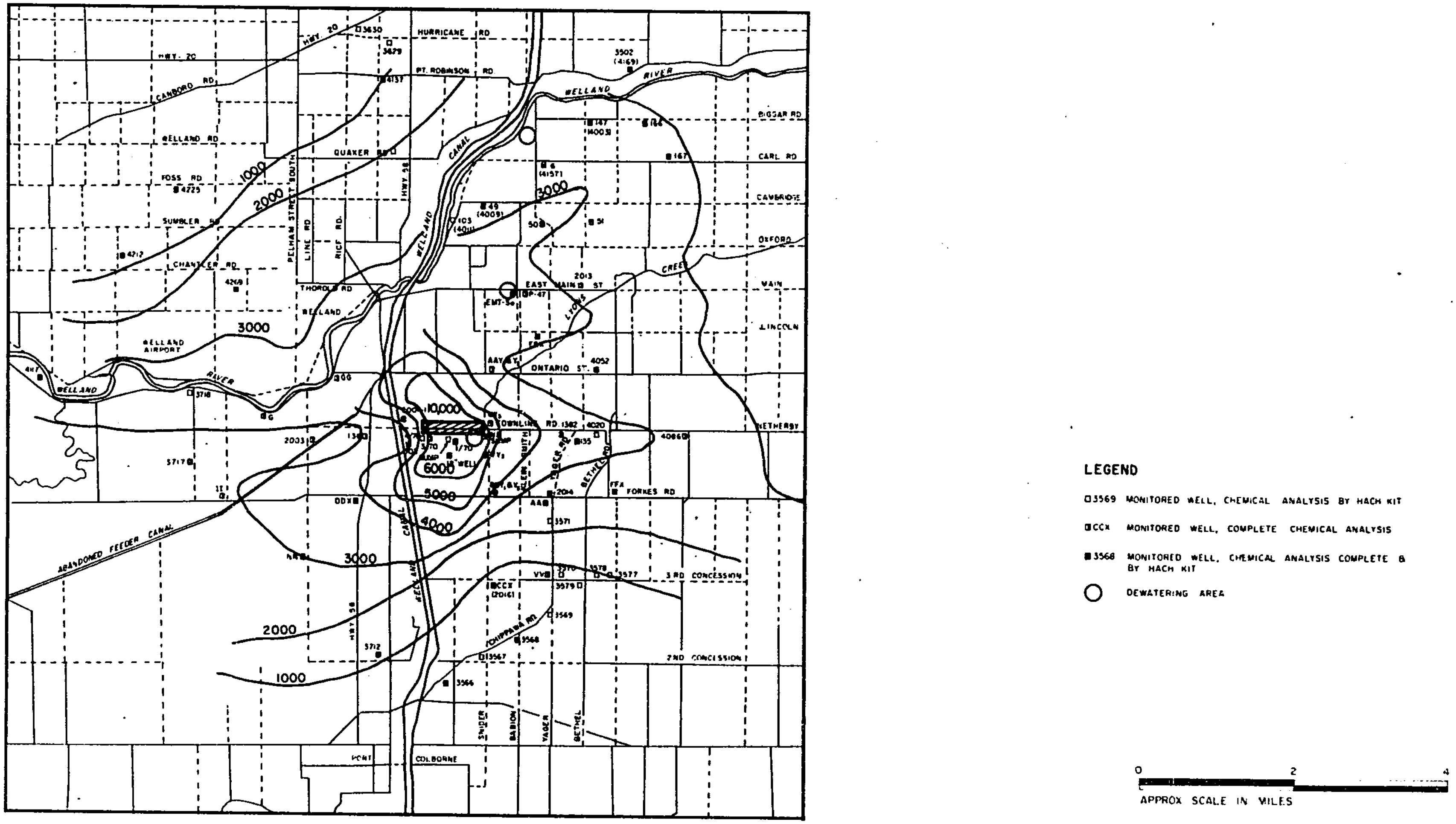
ate: April 1967

Seaways Pump Test Report

Well No.	T.D.S.	No.	Ca	Mg	Na	SO_4	cl	HCO_3
.Well	11,195	41	928	118	2,700	2,020	5,280	149

Table 1 - Preconstruction Water Analysis - 3

Well No.	No.	T.D.S.	Ca (ppm)	Mg (ppm)	Na (ppm)	SO_4 (ppm)	cl (ppm)	HCO_3 (ppm)
BH-135	18	3,672	586	185	306	1,950	560	85
-102	19	3,484	563	228	225	1,700	699	69
HH	20	3,693	664	179	271	1,650	860	69
501	21	4,287	630	263	510	1,950	775	159
12" Well	22	7,102	788	245	1,238	2,250	2,300	73
W-934	23	3,026	548	125	0.5	1,250	320	93
	Golders Report E.M.S. Tunnel Site - July 1968							
E.M.S. Tunnel	24	3,815	646	170	161	2,164	22	66



T.D.S. PRECONSTRUCTION

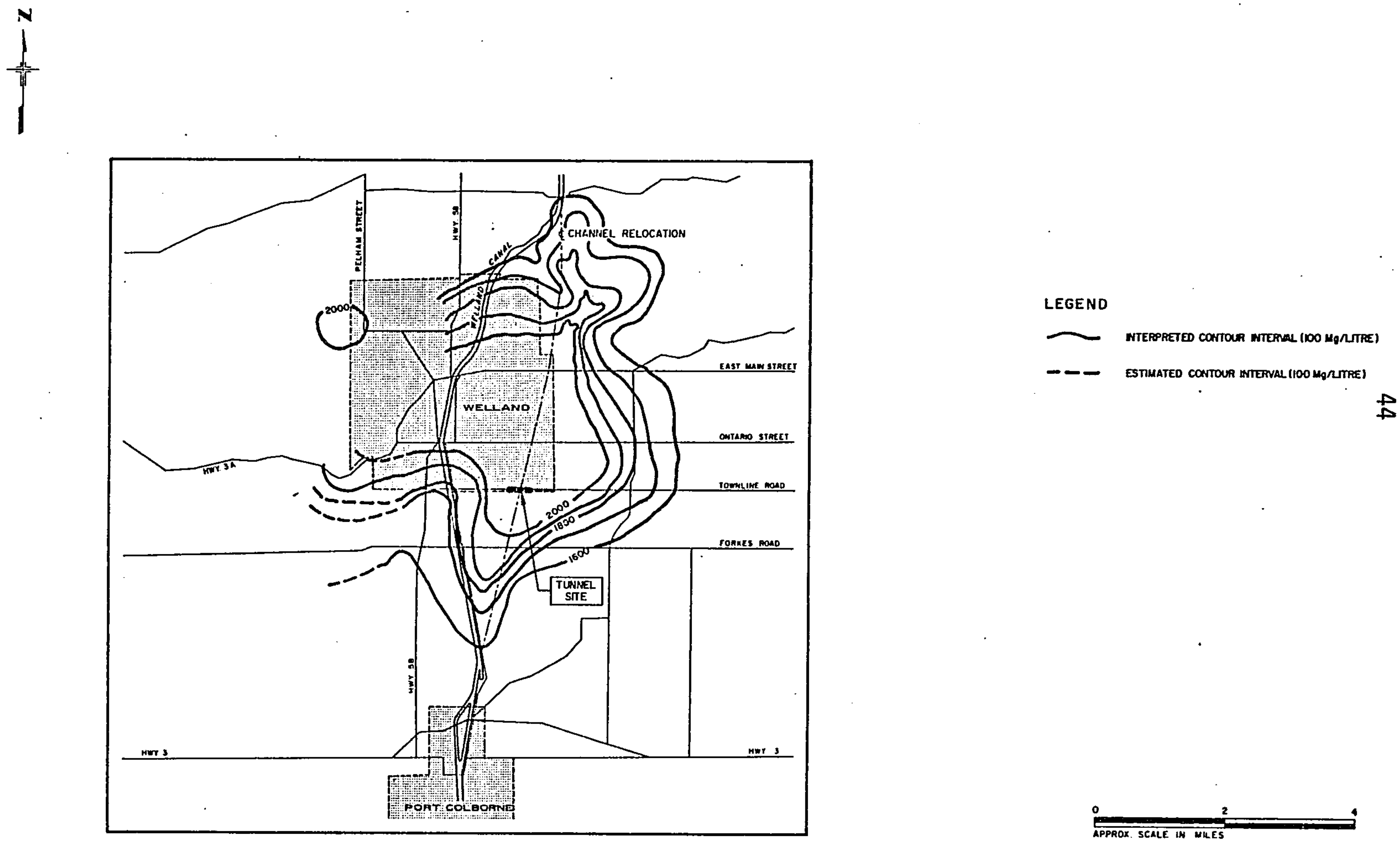
FIG 12

5.4 Concentration of Individual Ions

A pattern similar to total dissolved solids is observed for the concentration of sulphate ions in the groundwater (Figure 13). In the Fonthill and Port Colborne areas, the sulphate contents are generally in the range of 70-250 mg/l and increase progressively from 1,000 to 2,000 mg/l as soon as the water enters the Saline Formation. The increase of SO_4 entails an increase not only of Ca, but also of Mg. The concentration of Ca scarcely increases 500 mg/l except in the area where the high concentration of NaCl is observed (Figure 14). In the overburden wells, the sulphate contents of groundwater are reported to be between 103 to 218 mg/l (DHO Report). The relationship of Ca and SO_4 to total dissolved solids in the bedrock aquifer is well defined (Figure 15) for solutions containing minor amounts of NaCl.

In normal groundwater, the HCO_3 content rarely exceeds 500 mg/l. The concentration of HCO_3 remains normal and even tends to levels below normal when the concentration of $CaSO_4$ is high as a result of the influence of the solubility product of $CaSO_4$. Within the study area the concentration of HCO_3 varies from 80 to 289 mg/l, the higher concentration occurring in the recharge areas.

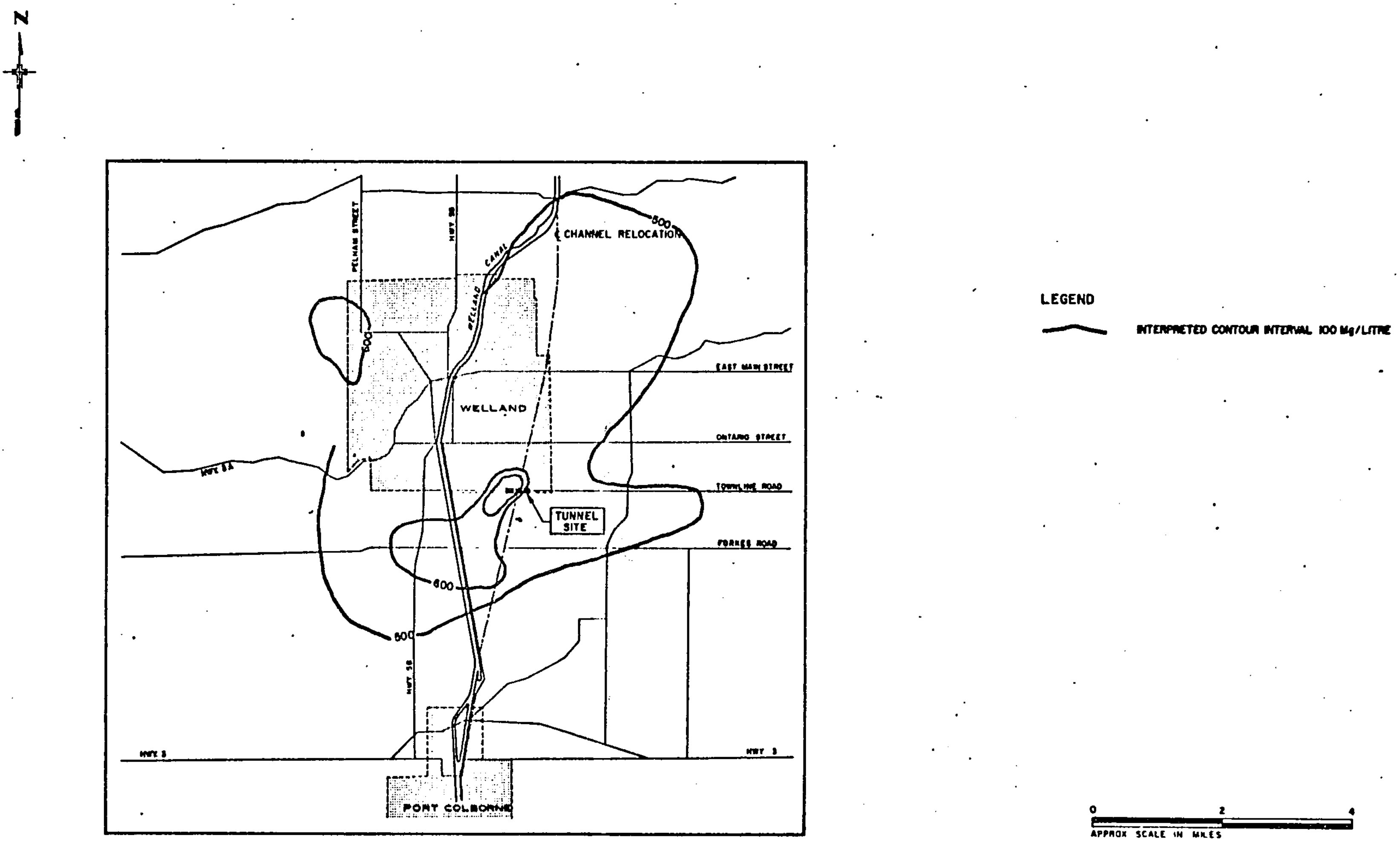
The chloride concentration showed an abnormal variation and an unusual increase. The chloride content in the groundwater is generally less than 100 mg/l, except in the central area near Welland City where it suddenly jumps up into thousands of mg/l. This localized abrupt increase (2,000 to 52,000 mg/l) suggested the possibility of mixing or intrusion of highly saline water of different chemical composition and origin.



SULPHATE CONTENT
IN GROUNDWATER
PRIOR TO CONSTRUCTION

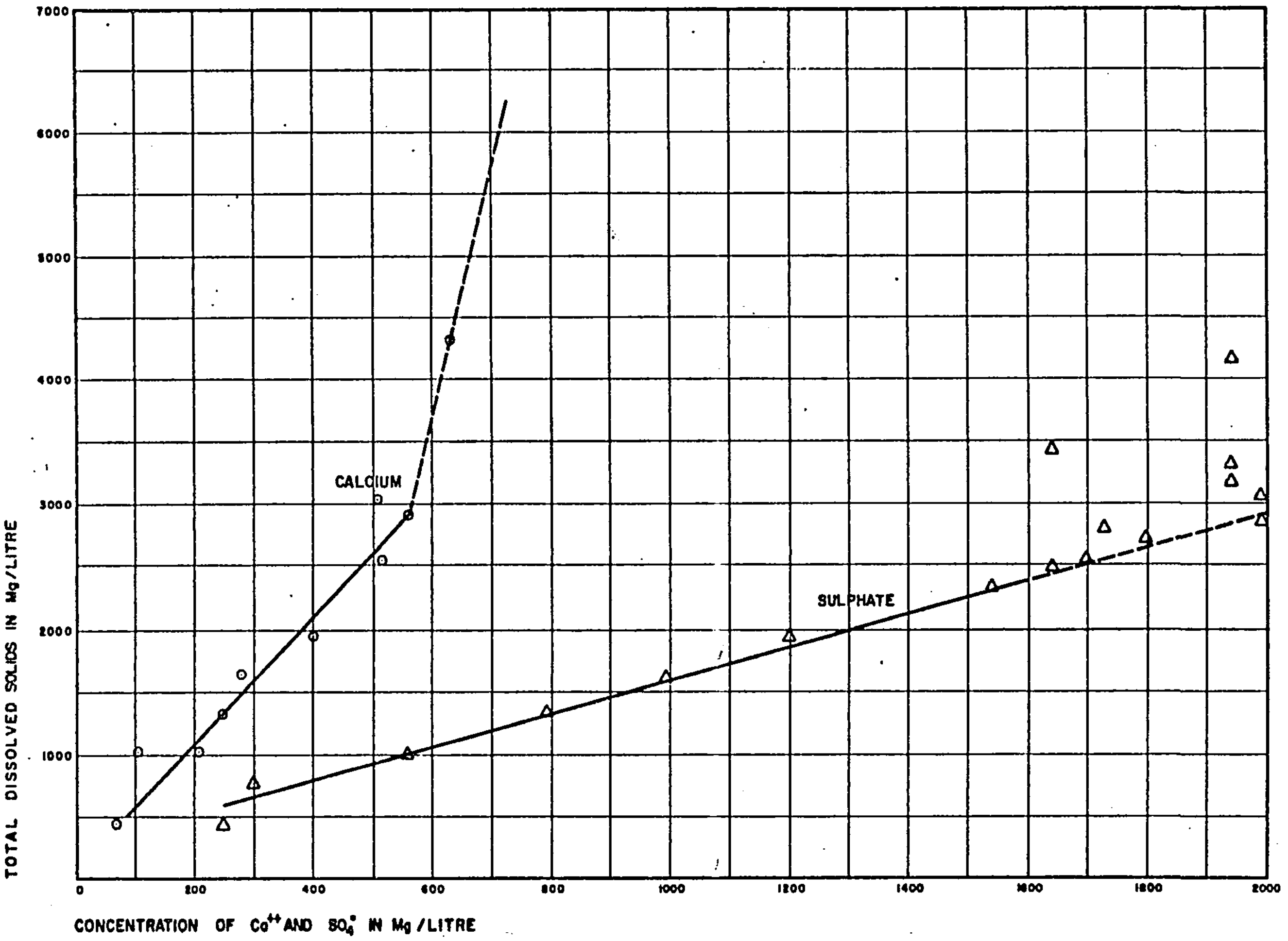
FIG:13

Fig. 13



CALCIUM CONTENT
IN GROUNDWATER
PRIOR TO CONSTRUCTION

FIG: 14



RELATION OF CALCIUM AND SULPHATE CONCENTRATIONS TO TOTAL DISSOLVED SOLIDS

FIG:15

5.5 Chemical Zonation

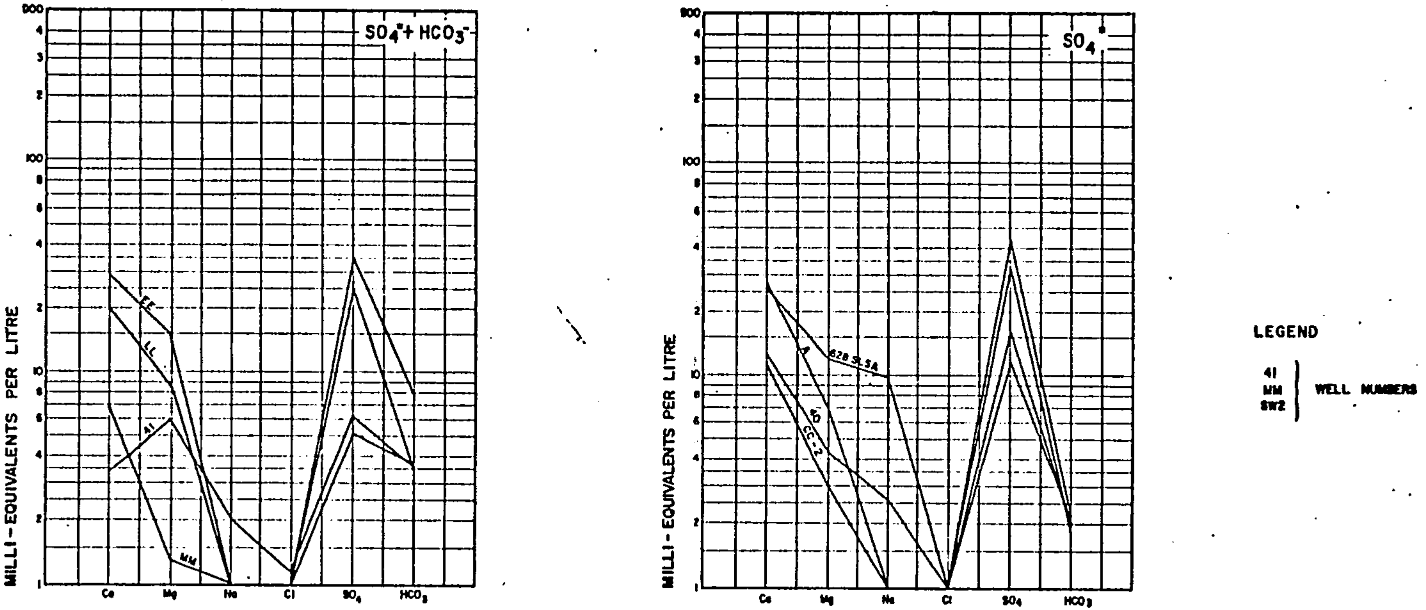
Chebotarev (1955), after studying the changes in chemical composition of natural waters from different geological environments concluded, "... the geochemical types of water change with the increase of the total salinity as well as with increasing depth." On a regional scale depending on the length of a flow system, the dominant ion in solution changes from a recharge area to discharge area in the following sequence:

$$HCO_3 \rightarrow HCO_3 + Cl \rightarrow Cl + HCO_3 \rightarrow \begin{array}{c} Cl + SO_4 \\ \text{or} \\ SO_4 + Cl \end{array} \rightarrow Cl \qquad \text{----------(i)}$$

The length to which this sequence advances depends on the length of the flow system. However, in predominantly gypsiferous environments the dissolution of $CaSO_4$ results in the following sequence (See Appendix I):

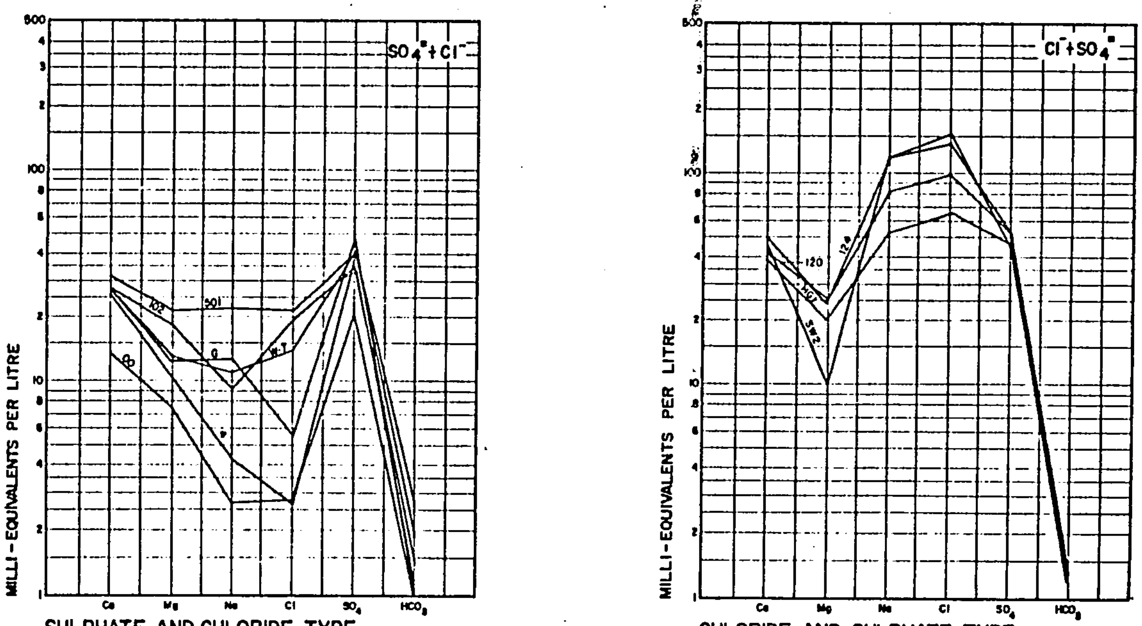
$$HCO_3 \rightarrow HCO_3 + SO_4 \rightarrow SO_4 + HCO_3 \rightarrow SO_4 \rightarrow SO_4 + Cl \rightarrow Cl + SO_4 \rightarrow Cl \qquad \text{----------(ii)}$$

On the basis of chemical analysis of groundwater, six characteristic hydrochemical types of waters were identified in the study area (Figure 16). The changes in water type occur with the increase in total dissolved solids in the following manner:



SULPHATE AND BICARBONATE TYPE

SULPHATE TYPE



SULPHATE AND CHLORIDE TYPE

CHLORIDE AND SULPHATE TYPE

CLASSIFICATION OF
GROUNDWATER

FIG:16

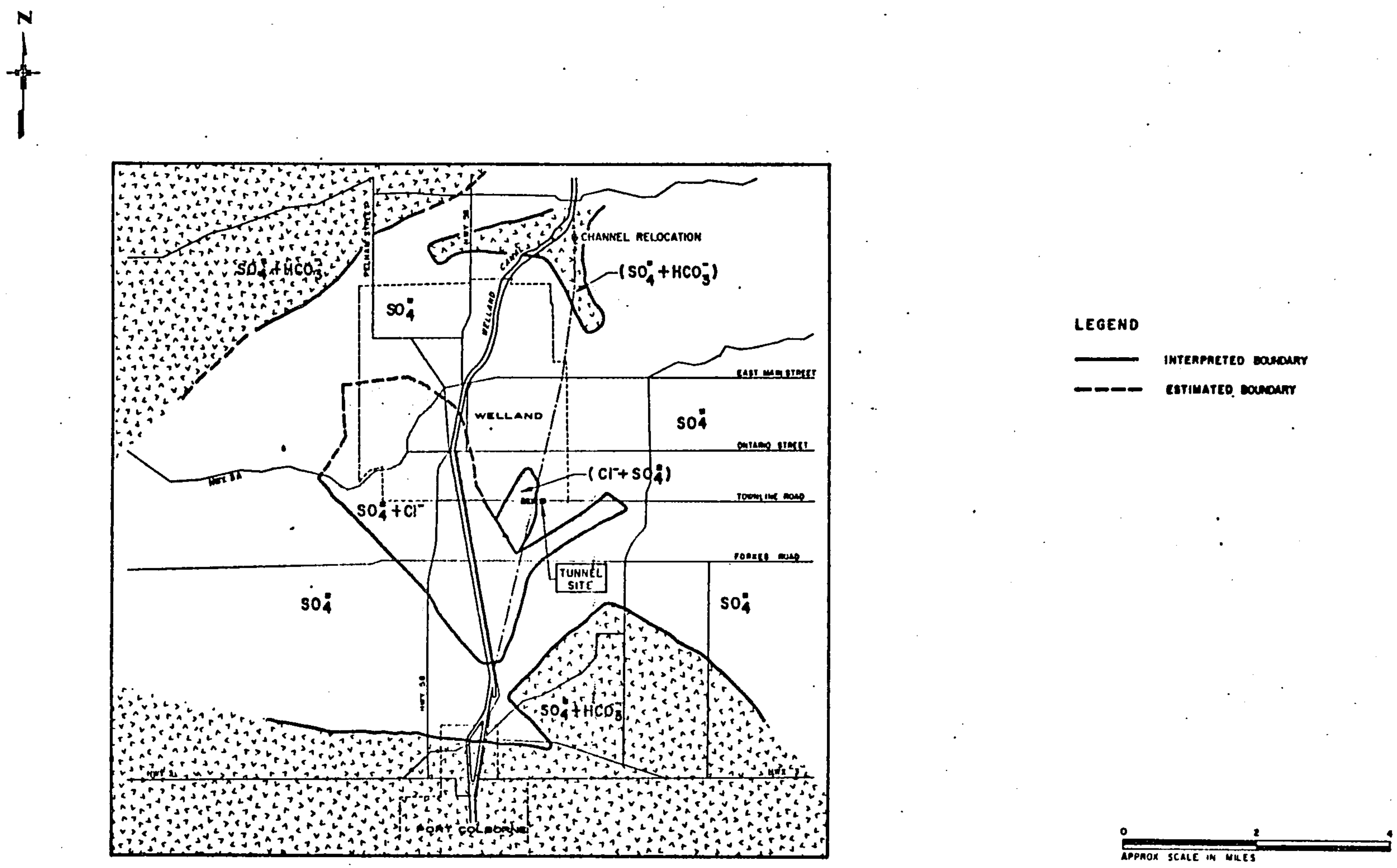
Water Type	Total Dissolved Solids
HCO_3, (Ca + Mg)	
$HCO_3 + SO_4$, (Ca + Mg)	197 - 500 mg/l
$SO_4 + HCO_3$, (Ca + Mg)	400 - 977 mg/l
SO_4, (Ca + Mg)	1,000 - 3,192 mg/l
SO_4 + Cl, (Ca + Na)	3,200 - 4,287 mg/l
Cl + SO_4, (Na + Ca)	7,000 - 11,000 mg/l

A progressive change in water type occurs from $HCO_3 + SO_4$ type water in the recharge areas of Fonthill and Port Colborne to a predominantly sulphate type ($SO_4 + HCO_3$ and SO_4) water further down gradient (Figure 17). At the southeast of the city of Welland, the presence of SO_4 + Cl type water reflects the changes in hydrochemical facies, primarily due to mixing of water of a different chemical composition from a different horizon. The ultimate change into Cl + SO_4 type at the tunnel site indicates the presence of a higher percentage of NaCl type brine in that area. Probably the previous pumping tests in the tunnel area resulted in the upward leakage of brine from deeper zones through some improperly plugged gas wells.

In predominantly gypsiferous environment at the study area the changes in water type from the recharge area to the tunnel site took place in the following sequence:

$$HCO_3 \rightarrow HCO_3 + SO_4 \rightarrow SO_4 + HCO_3 \rightarrow SO_4 \rightarrow SO_4 + Cl \rightarrow Cl + SO_4 \quad \text{-----(iii)}$$

The chemical character of the water reflects the combined effect of chemical activity between water, dolomite and gypsum, and the



ZONATION OF
GROUNDWATER TYPES
PRIOR TO CONSTRUCTION

FIG: 17

flow pattern within the aquifer. The predominantly HCO_3 type water and the lowest total dissolved solids in the areas of topographic and piezometric highs, confirmed the location of the recharge areas. Abundance of gypsum in the Salina Formation and the indications of its being dissolved was reflected by SO_4 dominant water in the central region.

CHAPTER VI

THEORETICAL ANALYSIS OF THE DISSOLUTION OF GYPSUM

6.1 Theory

The stability of gypsum when acted upon by groundwater is governed by a dynamic physicochemical equilibrium between the gypsum and the aqueous solution in contact with it. The possibility of dissolution and the magnitude of its occurrence can be determined by studying the sulphate-calcium equilibrium in the liquid phase. The equilibrium between solid ionic salt and its solution in water is governed by the solubility product expression.

The concept of chemical equilibrium is expressed by the Law of Mass Action, which states that the driving force of a chemical reaction to the right or left could be related to the concentrations of the reactants and products. When a system is at equilibrium, the rate to the right and left are equal. The chemical equation describing the solution of gypsum is:

$$CaSO_4.2H_2O = Ca^{++} + SO_4^{=} + 2H_2O \qquad \text{----------------(1)}$$

and the equilibrium constant for gypsum is:

$$K_{gyp} = \frac{\alpha Ca^{++}.\alpha SO4^{=}.\alpha 2H2O}{\alpha CaSO4.2H2O} \qquad \text{----------------(2)}$$

where α is activity. This thermodynamic constant varies with temperature, but for any given temperature is independent of the total pressure. The activity of a solid phase is equal to one; for dilute water the activity of water may also be considered equal to one, hence, equation (2) becomes:

$$K_{gyp} = \alpha Ca^{++} . \alpha SO_4^{=} \qquad \text{-----------------(3)}$$

where the K_{gyp} is the solubility product constant. Activity denoted by α is a measurement of the effective concentration of a reactant or a product in a chemical reaction. In a solution containing ions, the interaction among the solute particles results in deviation from ideal laws. The ionic interactions are essentially the electro-static attraction of ions of opposite charge, and hence, in dilute solutions the activity of an ion is smaller than its concentration. The activity is therefore a product of the concentration and the coefficient of activity:

$$\alpha_i = C_i \times \gamma_i$$

where C_i is the concentration in moles per liter and γ_i is the coefficient of activity. In dilute solutions both the concentration units of molality (moles per kilogram of solvent) and of molarity (moles per liter of solution) are generally used. However, the difference between molality and molarity in dilute aqueous solutions is slight compared to the uncertainties involved in measuring equilibrium constants or in estimating the activity coefficients.

The activity of ion species varies with the ionic strength which is defined as half the sum of the terms obtained by multiplying the concentration of each ionic species present in the solution by the square of its valence; thus,

$$U = \frac{1}{2} \sum_{i=1}^{N} C_i Z_i^2 \qquad \text{-----------------------(4)}$$

where C_i is the actual concentration of each ion in solution and Z_i is its valence.

In very dilute solutions activity is virtually equal to chemical concentration but for a moderate concentration non-ideality corrections are required and activity coefficient γ_i is based on the Debye-Huckel theory. The extended Debye-Huckel law (Glasstone, 1946) is:

$$\log \gamma_i = (-Az_i^2 U^{\frac{1}{2}}) / (1 + a_i BU^{\frac{1}{2}}) \qquad \text{-----------------------(5)}$$

where "a" is the effective diameter of the hydrated ion and B and A are temperature dependent constants (Garrel and Christ, 1965). Numerical values of "a" for Ca and SO_4 have been estimated to be 6 and 4 Angstrom units, respectively, by Kielland (1937). A modification of equation (5) was suggested by Guggenheim (Butler, 1962) and Davies (1936) by taking a fixed value of 3 Angstrom units for "a"

$$\log \gamma_i = - Az_i^2 (U^{\frac{1}{2}}/(1 + U^{\frac{1}{2}}) - bu) \qquad \text{---------------------(6)}$$

where "b" is a correction factor and can be taken as 0.2. Butler (1962) and Tanji and Doneen (1966) compared the theoretical values of activity coefficient with the experimental data and concluded that Davies' equation gave a reasonable estimate of the activity coefficient. At an ionic strength of 0.1 the error is less than 3 percent and at ionic strength of 0.5, the error is less than 8 percent. The solubility of gypsum increases with the amount of NaCl in the solution, from 1.70 g/kg at 14 degrees C when NaCl is absent, to 7.2 g/kg for a concentration of NaCl of 2.25 mole/liter (Schoeller, 1962). If the value of solubility product constant K_{gyp} and the initial concentration of ions in solution is known, it is possible to make solubility calculations by utilizing the above indicated equations. The calculated activities of Ca and SO_4 can be used to obtain the ion activity product K_{iap}. The comparison of K_{iap} with the equilibrium constant would indicate the departure from equilibrium of the water with respect to gypsum. The ratio of (K_{iap}: K_{gyp}) indicates the percentage of saturation; ratio of one is 100 percent saturation.

If x be the amount of Ca^{++} and SO_4 which dissolve in a solution whose initial concentration of Ca^{++} and SO_4 is M_{Ca} and M_{SO4} moles per liter, then

$$C_{Ca} = M_{Ca} + x \qquad \text{-------------------(7)}$$

$$C_{SO4} = M_{SO4} + x \qquad \text{-------------------(8)}$$

when equation (7) and (8) are combined with equation (3) it yields, upon rearrangement,

$$x^2 + (M_{Ca} + M_{SO_4})\,x + (M_{Ca}\ \ M_{SO_4} - K_{gyp}/\gamma^2) = 0 \qquad \text{---------------(9)}$$

from which x can be calculated.

6.2 Results and Discussion

The solubility calculations were made by solving equations 3, 4, 6 and 9 in a series of successive approximations. This calculation is lengthy. For convenience the general case was programmed for IBM computer.

As pointed out earlier, in order to calculate the solubility of gypsum it was necessary to establish a reasonable value of K_{gyp}. The temperature of groundwater in the study area is generally steady at 11 degrees C with an occasional variation of 1 degree C. Although the difference in solubility of gypsum at 11 degrees C and 14 degrees C is slight, however, as a safety factor the experimental results from literature at 14 degrees C are used to determine the value of K_{gyp}. The values of solubility of $CaSO_4$ vary with temperature in the following manner:

Temperature	(Ca) (SO_4) Moles/Liter
0 degrees C	1.67×10^{-4}
10 degrees C	1.99×10^{-4}
18 degrees C	2.19×10^{-4}
30 degrees C	2.37×10^{-4}
55 degrees C	2.34×10^{-4} (Schoeller 1962)

Unfortunately, most of the experimental and theoretical data reported by various authors is related to 25 degrees Centigrade temperature only. The solubility data compiled by Longenecker and Lyerly (1959) is extensively used in agricultural research. The values of 2.45×10^{-5}

(Moreno and Osborn, 1963) and 2.4 x 10^{-5} (Latimer, 1952) for K_{gyp} have been generally used for computation of solubility at 25 degrees C. These values are considerably low because the ionic strength of aqueous salt solution generally exceeds concentrations that normally occur in agricultural waters and in soil solutions (Tanji and Doneen, 1966). By using distilled water on soil samples, Sheternina (1962) determined the K_{gyp} values which varied from 2.8 x 10^{-5} to 3.2 x 10^{-5}. Levcheko (1949) measured experimentally as well as calculated theoretically the solubility of gypsum in NaCl solution at 25 degrees C.

NaCl Mole/Liter	$CaSO_4$ Mole/Liter	Ionic Strength	Coefficient of Activity
0	.0153	.0614	.40
0.0122	.0165	.078	.371
0.097	.0231	.189	.267
0.269	.0320	.396	.192

For dissolution of $CaSO_4$ in pure water the K value determined was

$$K_{gyp} = (0.0153)^2 (0.4)^2 = 3.7 \times 10^{-5}$$

Schoeller (1962) reported the following experimental data on the solubility of gypsum at 14 degrees C.

NaCl Mole/Liter	$CaSO_4$ in Me/l	U	$(Ca)(SO_4)$ Moles/Liter
0	25	.05	1.56×10^{-4}
.05	34	.118	2.90×10^{-4}
.1	41	.182	4.20×10^{-4}
.2	50	.30	6.25×10^{-4}

The values of activity coefficients calculated from Davies equation at various ionic strengths, Table 2 and Figure 18, indicate that at ionic strength .05 the activity coefficient is .45, therefore

$$K_{gyp} = (.0125)^2\ (.45)^2 = 3.2 \times 10^{-5}$$

This value of equilibrium constant obtained from the laboratory data and theoretical calculations appear to be quite appropriate for the purpose of studying the solubility of gypsum in the study area. However there are many other factors (See Appendix I) in a hydrogeological environment which might in some cases influence this value of K, obtained from laboratory data. Therefore, the K value determined above was verified by analyzing the actual data obtained from the chemical analysis of the groundwater from the Welland area.

The concentration of $CaSO_4$ in the study area ranged from .0005 to .026 mole/liter and of NaCl from .0001 to .118 moles/liter with ionic strength varying from .0034 to .24. The additional concentration increases the ionic strength which decreases the activity coefficient and therefore allows more gypsum to go into solution. The graph showing the relationship of $CaSO_4$ concentration in the Welland area and the ionic strength of the aqueous solution (Figure 19) clearly demonstrates that the concentration of $CaSO_4$ in groundwater increases rapidly until at $U = .073$ and $CaSO_4 = .0143$ or product of ionic concentration $(Ca)\ (SO_4) = 1.99 \times 10^{-5}$, saturation is reached. Further increase beyond this point is very slow and occurs only with the increase in NaCl concentration. The curve NaCl vs $CaSO_4$ (Figure 20) also confirms the above observation. Since the activity coefficient at .073 ionic strength is

TABLE 2

Values of Coefficient of Activity Calculated from Davies Equation

Well No.	Ionic Strength	Coefficient of Activity	(Ca) (SO_4) mole/liter	Kiap
1	0.1177938E-01	0.6462895E-00	0.4476025E-05	0.1869591E-05
2	0.1995362E-01	0.5785641E-00	0.2179629E-05	0.7296010E-06
3	0.1583363E-01	0.6088855E-00	0.8887180E-05	0.3294846E-05
4	0.1923274E-01	0.5834407E-00	0.5449074E-05	0.1854881E-05
5	0.2736140E-01	0.5361152E-00	0.3225332E-04	0.9270231E-05
6	0.4544118E-01	0.4671078E-00	0.7187585E-04	0.1568257E-04
7	0.3636524E-01	0.4973720E-00	0.5334897E-04	0.1319740E-04
8	0.5536464E-01	0.4406160E-00	0.1239275E-03	0.2405957E-04
9	0.6308824E-01	0.4233938E-00	0.2204019E-03	0.3950974E-04
10	0.8164632E-01	0.3903731E-00	0.2406155E-03	0.3666765E-04
11	0.8502400E-01	0.3853276E-00	0.2703776E-03	0.4014495E-04
12	0.8993906E-01	0.3784087E-00	0.2737378E-03	0.3919734E-04
13	0.2406048E-00	0.2770486E-00	0.4749515E-03	0.3645531E-04
14	0.2122829E-00	0.2873744E-00	0.5723860E-03	0.4726993E-04
15	0.2212724E-00	0.2838554E-00	0.6694575E-03	0.5394076E-04
16	0.3414748E-02	0.7795054E-00	0.2106974E-06	0.1280258E-06
17	0.7215030E-02	0.7039362E-00	0.1427137E-05	0.7071839E-06
18	0.1002637E-00	0.3652965E-00	0.2965073E-03	0.3956637E-04

Table 2 - Values of Coefficient of Activity Calculated from Davies Equation - 2

Well No.	Ionic Strength	Coefficient of Activity	$(Ca)(SO_4)$ mole/liter	Kiap
19	0.9751934E-01	0.3686103E-00	0.2483476E-03	0.3374385E-04
20	0.1007601E-00	0.3647095E-00	0.2842858E-03	0.3781369E-04
21	0.1169490E-00	0.3473921E-00	0.3187705E-03	0.3846963E-04
22	0.1662246E-00	0.3099865E-00	0.4600575E-03	0.4420767E-04
23	0.6891006E-01	0.4119264E-00	0.1777434E-03	0.3016010E-04
24	0.9558010E-01	0.3710237E-00	0.3627380E-03	0.4993399E-04
25	0.8562934E-01	0.3844494E-00	0.2654786E-03	0.3923809E-04
26	0.7292634E-01	0.4046523E-00	0.2162970E-03	0.3541721E-04
27	0.7632500E-01	0.3988559E-00	0.2360032E-03	0.3754480E-04
28	0.8205336E-01	0.3897519E-00	0.2415016E-03	0.3668565E-04
29	0.7204485E-01	0.4062081E-00	0.2052160E-03	0.3386165E-04
30	0.7308263E-01	0.4043787E-00	0.2258531E-03	0.3693198E-04
31	0.8189356E-01	0.3899953E-00	0.2532520E-03	0.3851867E-04
32	0.7204187E-01	0.4062133E-00	0.2258178E-03	0.3726203E-04
33	0.8132732E-01	0.3908626E-00	0.2498690E-03	0.3817337E-04
34	0.7836956E-01	0.3955151E-00	0.2462529E-03	0.3852187E-04
35	0.7905036E-01	0.3944256E-00	0.2463497E-03	0.3832500E-04
36	0.9332240E-01	0.3739123E-00	0.2801016E-03	0.3916110E-04
37	0.7810235E-01	0.3959457E-00	0.2410047E-03	0.3778301E-04

Table 2 - Values of Coefficient of Activity Calculated from Davies Equation

Well No.	Ionic Strength	Coefficient of Activity	(Ca) (SO4) mole/liter	Kiap
38	0.7782209E-01	0.3963994E-00	0.2259009E-03	0.3549637E-04
39	0.7981634E-01	0.3932134E-00	0.2244499E-03	0.3470370E-04
40	0.7230949E-01	0.4057387E-00	0.2149789E-03	0.3539064E-04
41	0.2324214E-00	0.2798111E-00	0.4864102E-03	0.3808310E-04

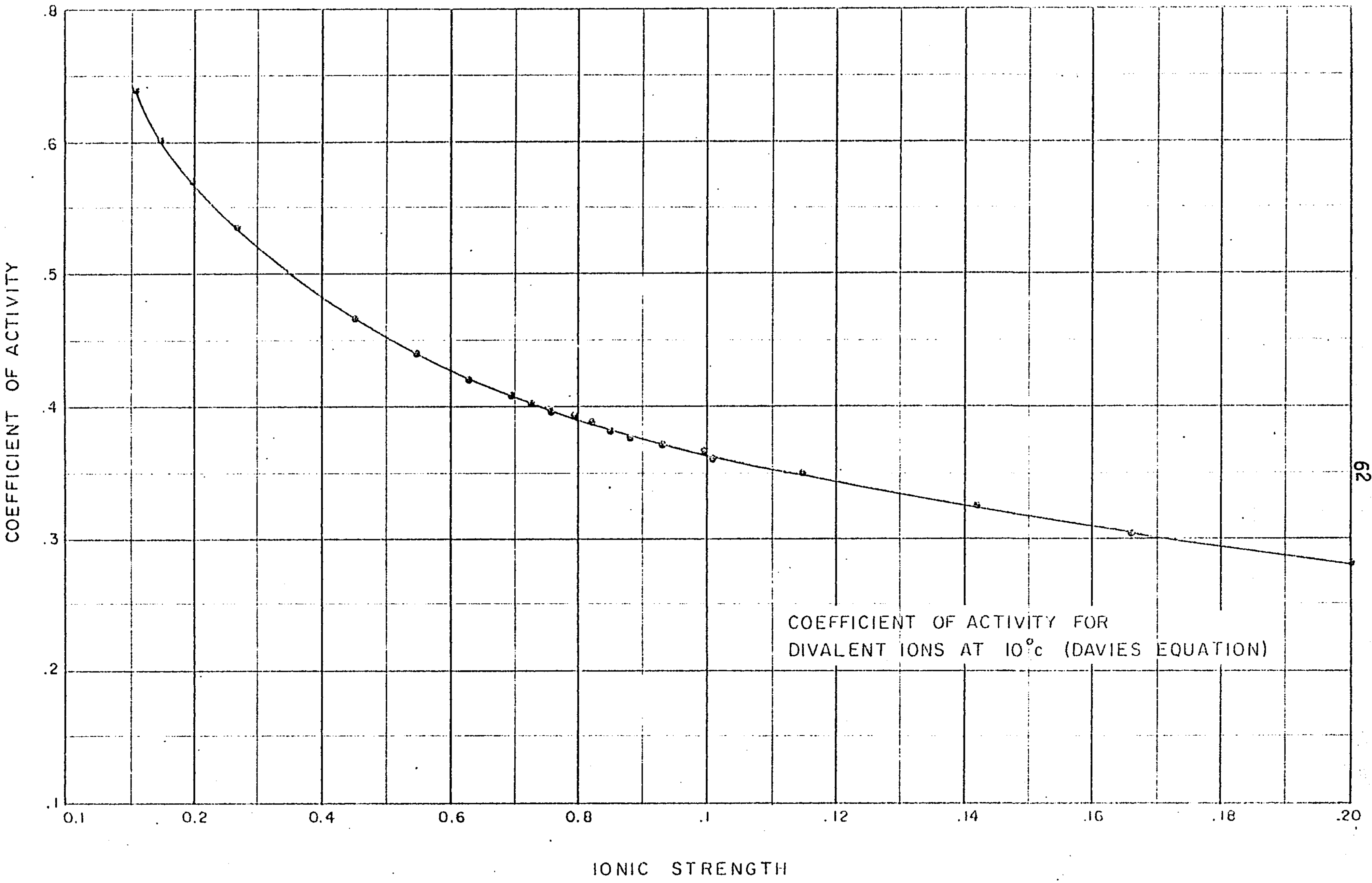
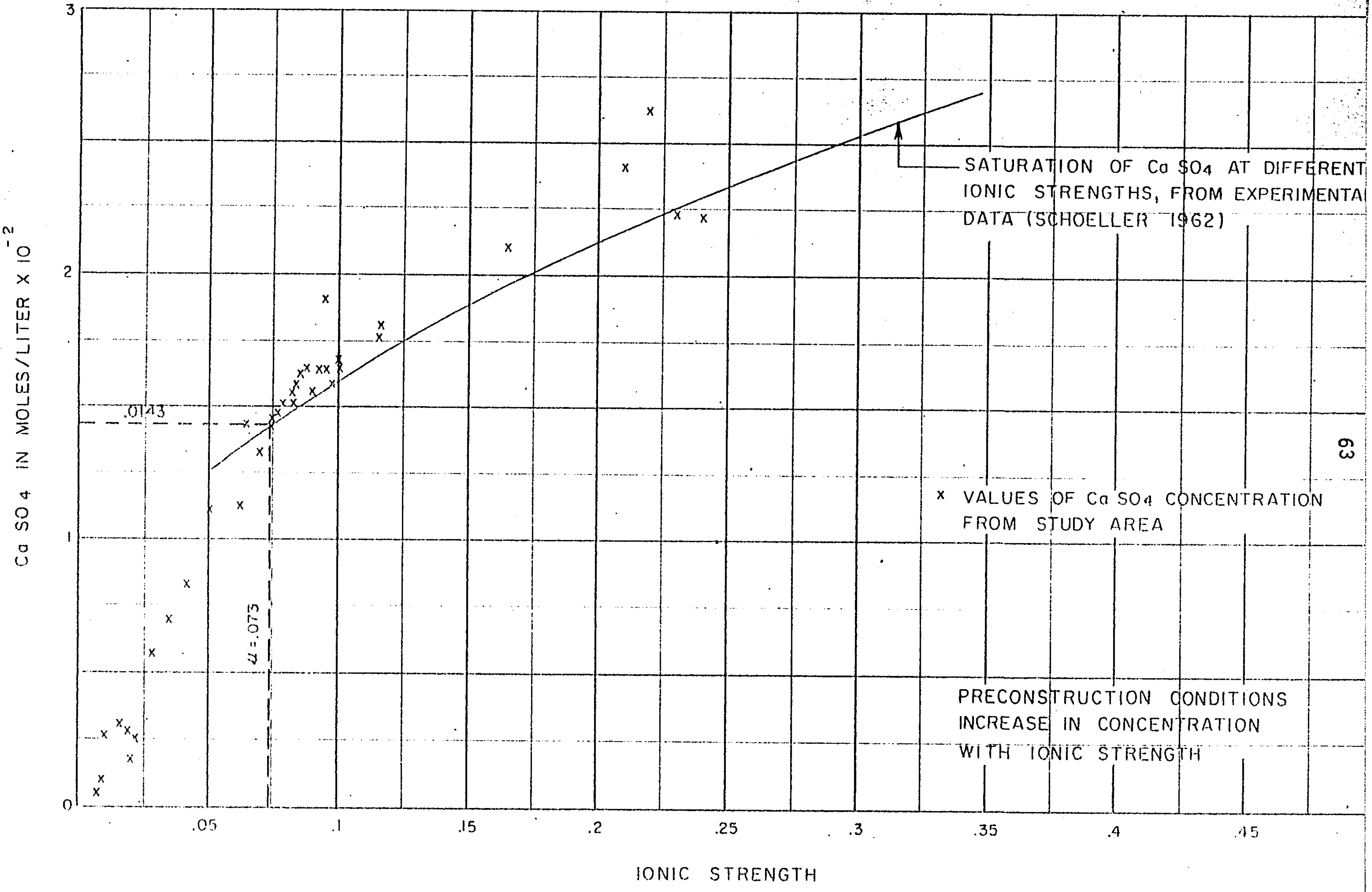
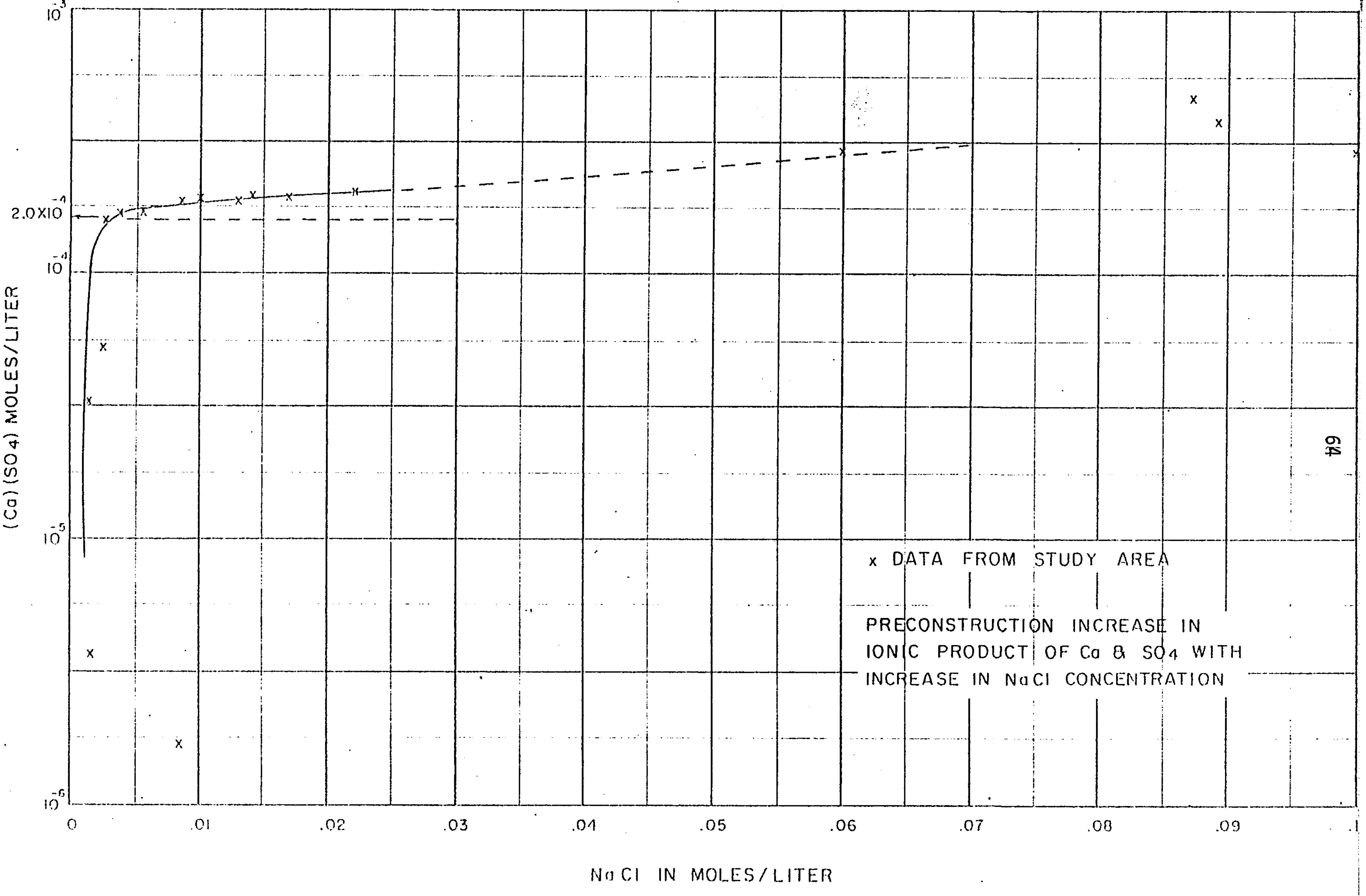

COEFFICIENT OF ACTIVITY FOR
DIVALENT IONS AT 10°c (DAVIES EQUATION)
COEFFICIENT OF ACTIVITY
.8
.6
.5
.4
.3
.2
.1
0.1
0.2
0.4
0.6
0.8
.1
.12
.14
.16
.18
.20
IONIC STRENGTH

FIG:18


Ca SO4 IN MOLES/LITER X 10^{-2}
3
2
1
0
.0143
μ=.073
.05
.1
.15
.2
.25
.3
.35
.4
.45
IONIC STRENGTH
SATURATION OF Ca SO4 AT DIFFERENT IONIC STRENGTHS, FROM EXPERIMENTAL DATA (SCHOELLER 1962)
x VALUES OF Ca SO4 CONCENTRATION FROM STUDY AREA
PRECONSTRUCTION CONDITIONS INCREASE IN CONCENTRATION WITH IONIC STRENGTH


10^{-3}
2.0×10^{-4}
10^{-4}
10^{-5}
10^{-6}
(Ca) (SO4) MOLES/LITER
0
.01
.02
.03
.04
.05
.06
.07
.08
.09
.1
NaCl IN MOLES/LITER
x DATA FROM STUDY AREA
PRECONSTRUCTION INCREASE IN IONIC PRODUCT OF Ca & SO4 WITH INCREASE IN NaCl CONCENTRATION

equal to .4, hence

$$K_{gyp} = (1.99 \times 10^{-4})\ (.4)^2 = 3.2 \times 10^{-5}$$

which proves that the value of $K = 3.2 \times 10^{-5}$ is a valid and reasonable estimate for the conditions in the Welland area. The water samples which plot below the solubility curve (Figure 19) are unsaturated with respect to gypsum and have K_{iap} value less than 3.2×10^{-5}. The calculated values of K_{iap}, ionic strength, activity coefficient and ionic product of Ca and SO_4 in moles/liter are shown in Table 2.

To determine the relative aggressiveness of groundwater towards gypsum, in the case of unsaturated water the value of deficit in saturation was calculated by solving equation (9). The results are shown in Table 3.

Because all systems in nature tend toward equilibrium, it is evident that where water is undersaturated with respect to a mineral, that mineral is being dissolved. However, supersaturation commonly occurs in groundwater (Schoeller, 1959) and the natural controls on rates and locations of precipitation are poorly understood (Davis 1968). Because of kinetic effects one cannot categorically say that, where the water is supersaturated with respect to a mineral, the mineral is necessarily being precipitated.

TABLE 3

Deficit in $CaSO_4$ Saturation

Well No.	Deficit in Saturation mole/liter	mg/l
1	0.7661180E-04	1618
2	0.9559758E-04	1686
3	0.8631349E-04	1496
4	0.9400620E-04	1550
5	0.1113355E-03	1142
6	0.1466613E-03	755
7	0.1293562E-03	920
8	0.1648274E-03	400
16	0.5266373E-04	1850
17	0.6457781E-04	1756
23	0.1885865E-03	103

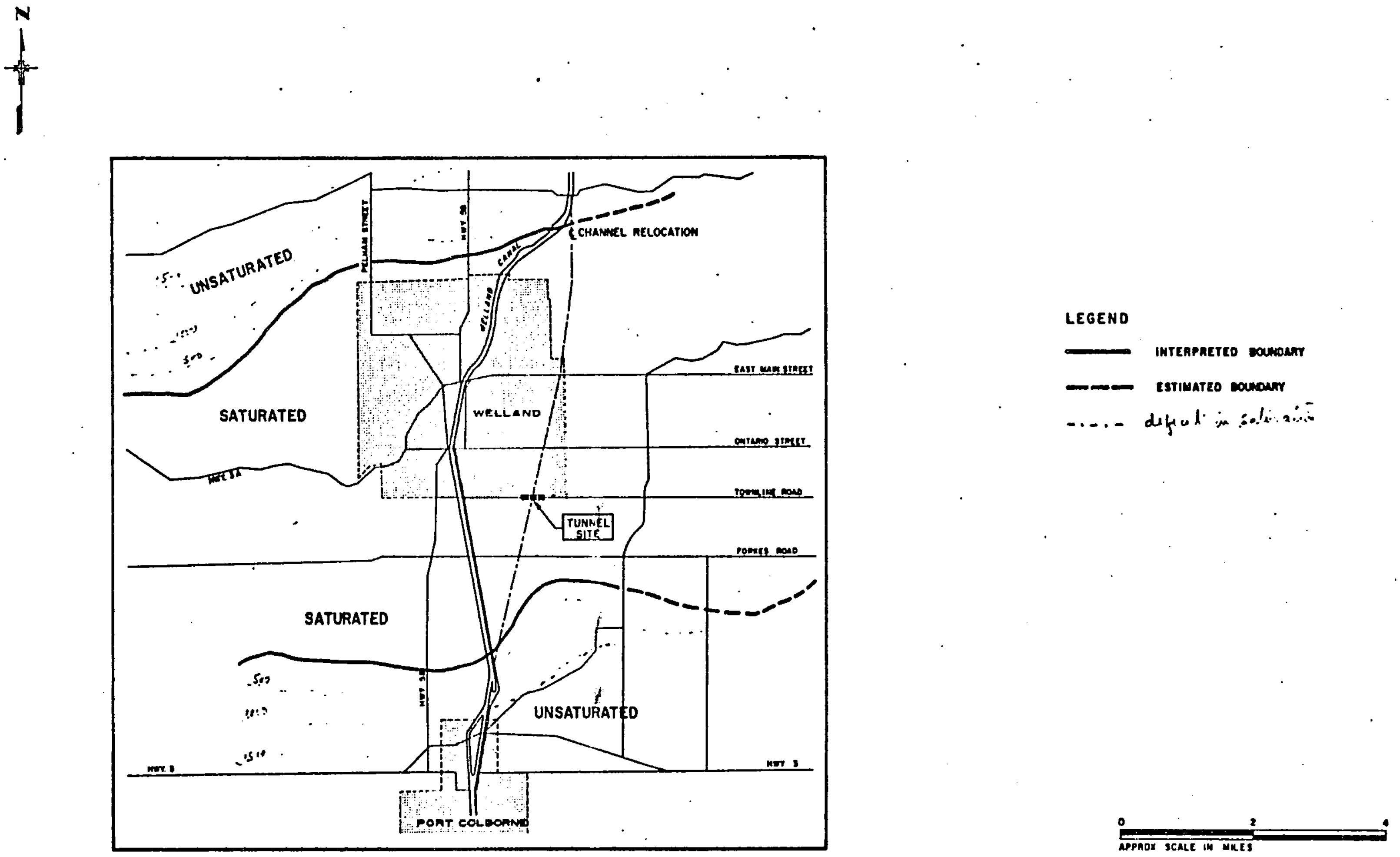
CHAPTER VII

FIELD APPLICATION OF THEORETICAL SOLUTION

7.1 Application to Conditions Prior to Construction

As pointed out earlier it is prerequisite to have a fairly good knowledge of the geology, geochemistry and hydrology of the area under investigation in order to apply meaningfully the theoretical solution to the field conditions. In the final analysis the conclusions drawn from both the theoretical study and the field measurements should be considered together in order to arrive at a more rational solution.

The solubility calculations indicate that some of the water samples are saturated with respect to gypsum and some are undersaturated. The process of solution in a hydrogeological environment is directly related to the geology and the groundwater flow system. This relationship, which can help to establish the validity of the theoretical calculations, can be determined by plotting the results of computations on the map of the study area. Furthermore, in order to establish the feasibility of the project or to monitor the future changes in hydrochemical processes, it is essential to determine the approximate position of the boundary between saturated and unsaturated aggressive water. This was achieved by plotting the results of the gypsum equilibrium on the map of the Welland region as shown in Figure 21.



BOUNDARY OF GYPSUM - SATURATED GROUNDWATER PRIOR TO CONSTRUCTION

FIG: 21

As the rate of solution is proportional to the saturation deficit, the relative degree of aggressiveness of undersaturated water in the zone of active solution was determined by plotting the values of deficit on the map of the study area.

The distribution of the departure from equilibrium with respect to gypsum as shown in Figure 21, indicates that in the Welland area $CaSO_4$ concentration under the natural gradient continues to increase in the direction of flow. The progressive decrease in the aggressiveness of the groundwater takes place with the increase in distance from recharge areas. The principal recharge locations and their surrounding areas contain water undersaturated with respect to gypsum, while water in the central zone of the study area is saturated and hence in a state of equilibrium with the solid phase. This indicates that the groundwater flow pattern is a major control on the distribution of areas where solution processes are occurring. The area occupied by saturated water is underlain by the Salina Formation.

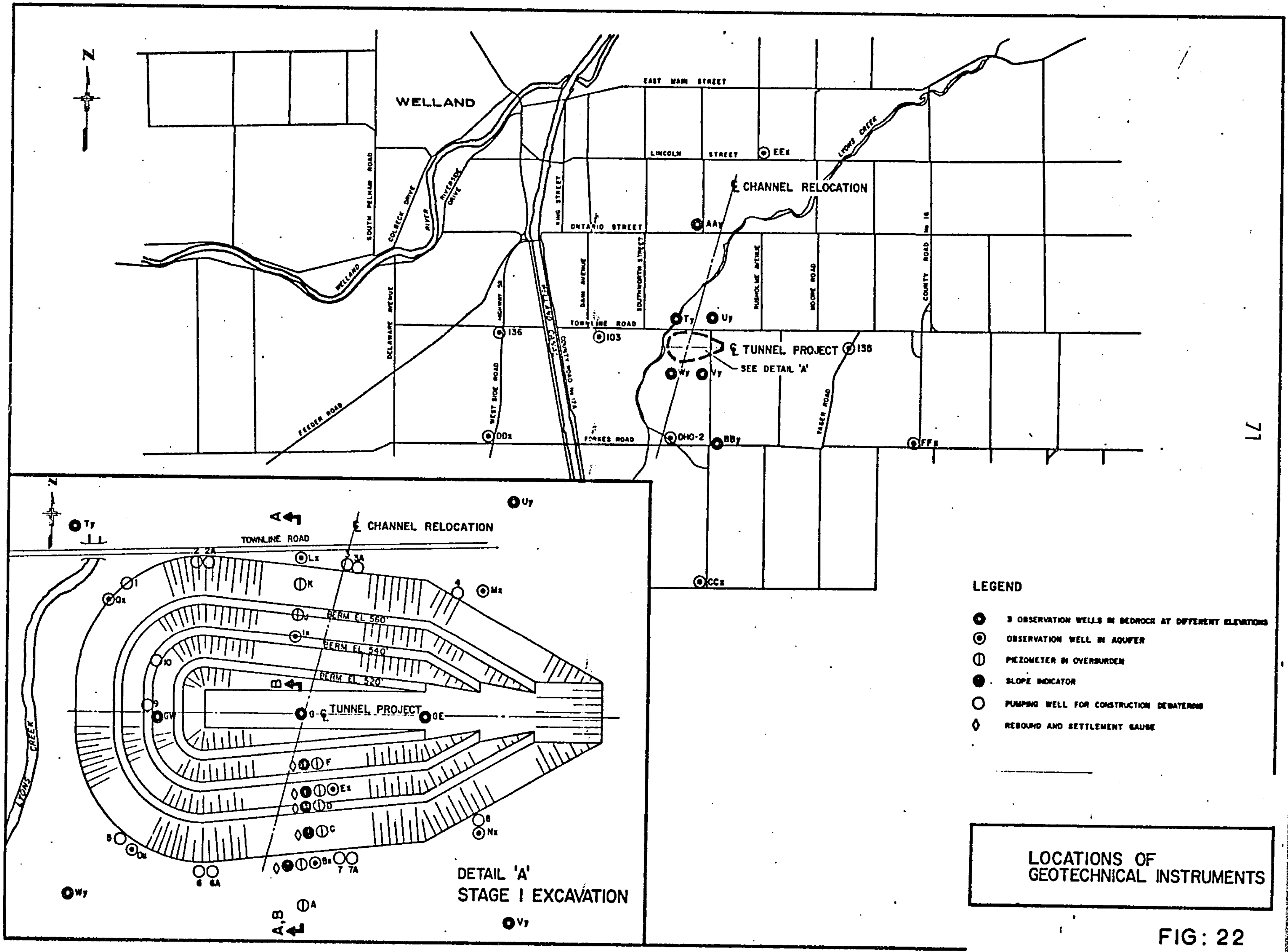
Since the Townline Rail/Road Tunnel site is situated in the middle of the Salina Formation and the saturated zone, it is, therefore, evident that the groundwater at the tunnel site is in a state of equilibrium and the gypsum is not being leached. This conclusion was substantially confirmed by later field investigations which consisted of borehole photography and 36-inch diameter exploratory holes as described in Chapter 2.

7.2 Monitoring System

The monitoring wells may be located near the potentially mobile boundary or near the project site. A monitoring well is used to detect hydrologic or hydrochemical changes with time. The object of monitoring wells is to determine whether the unsaturated water will move towards the tunnel foundation. A desirable goal is to know the degree of aggressiveness of groundwater at many point or to have a map showing the distribution of saturated and undersaturated water and maps showing prior distribution of these zones.

In the interest of economy it is necessary to limit the monitoring system to the minimum that will give satisfactory answers. In many cases the position of the strategic segment of the boundary between saturated and undersaturated water and the degree of movement of this boundary will suffice.

The monitoring system in the study area consisted of 14 observation wells in addition to instrumentation carried out at the project site, which included a number of piezometers in the bedrock and overburden, rebound and settlement gauges, and slope indicators as shown in Figure 22. Each observation well in the "y" series, such as By and Vy, etc., consists of groups of 3 wells at depths of approximately 10, 50 and 100 feet in rock. These observation wells were installed to determine the head relationship between various permeable zones; the effect of future dewatering on lower pervious zones; and the chemical character of the groundwater at depth. The observation wells were constructed with shorter sections of open holes below the



LOCATIONS OF GEOTECHNICAL INSTRUMENTS

FIG: 22

ends of the raisers. In order to avoid connecting two or more pervious zones, holes were pressure tested and sealed with bentonite.

The observation wells marked "X" such as EEX and NX, etc., were installed in the main aquifer to study the movement of the saturation boundary, and changes in the water level. The results of the groundwater instrumentation have been incorporated and discussed in the following sections.

7.3 Effects of Construction

In order to prevent bottom heave during excavation for the tunnel foundation and to ensure long-term stability of the structure foundation and overburden slopes, depressurization of the bedrock aquifer was required, both during and following the construction. The depressurization system designed by the Contractor and used for the excavation stages consisted initially of 8 deep wells located around the perimeter of the excavated area. As the excavation reached bedrock, dewatering and depressurization were effected entirely by pumping from the sump opened up at the west end of the excavation area. Almost at the same time a deep-well dewatering system was installed at the Welland River syphon site. Pumping at both sites started towards the end of 1968.

The monitoring system provided the means necessary for obtaining data upon which an evaluation could be made of the physical and chemical changes in the groundwater occasioned by the construction dewatering.

7.3.1 Groundwater

The rate of pumping at both sites, Townline Tunnel and Welland River syphon, varied during the year 1969-1970, from approximately 800 to 1,600 gpm and 500 to 1,500 gpm respectively. The original pattern of groundwater potentials indicated a normal gravity flow system with water moving downward and laterally from areas of recharge toward discharge in the vicinity of the streams. As a result of the pumping at the dewatering sites, this normal pattern has been altered so that most of the water now moves towards the centres of dewatering. The recharge under the natural conditions was retarded as the discharge at the bottom of Welland River was restricted due to the presence of thick lacustrine deposits. Now with two groundwater sinks in the area discharging significant quantities the influx of flow has increased considerably. A steep gradient has been established between the recharge areas and the centre of pumping. Deep cones of depression have developed around the centre of pumping and the water level has been lowered as much as 10 feet at a distance of 6 to 7 miles in a westerly direction. Because of boundary conditions in the northerly and southeasterly directions the decline in water level is about 10 feet at a distance of 2 to 3 miles (Figure 23). The interference between the two dewatering sites is discussed in detail by Farvolden and Nunan (1970). However, the lowering of the water level in some places has reversed the hydraulic gradient between the Welland River, Welland Canal and the areas of withdrawal. Hence, within the zone of influence, the Welland River and Canal might locally serve as recharge sources.

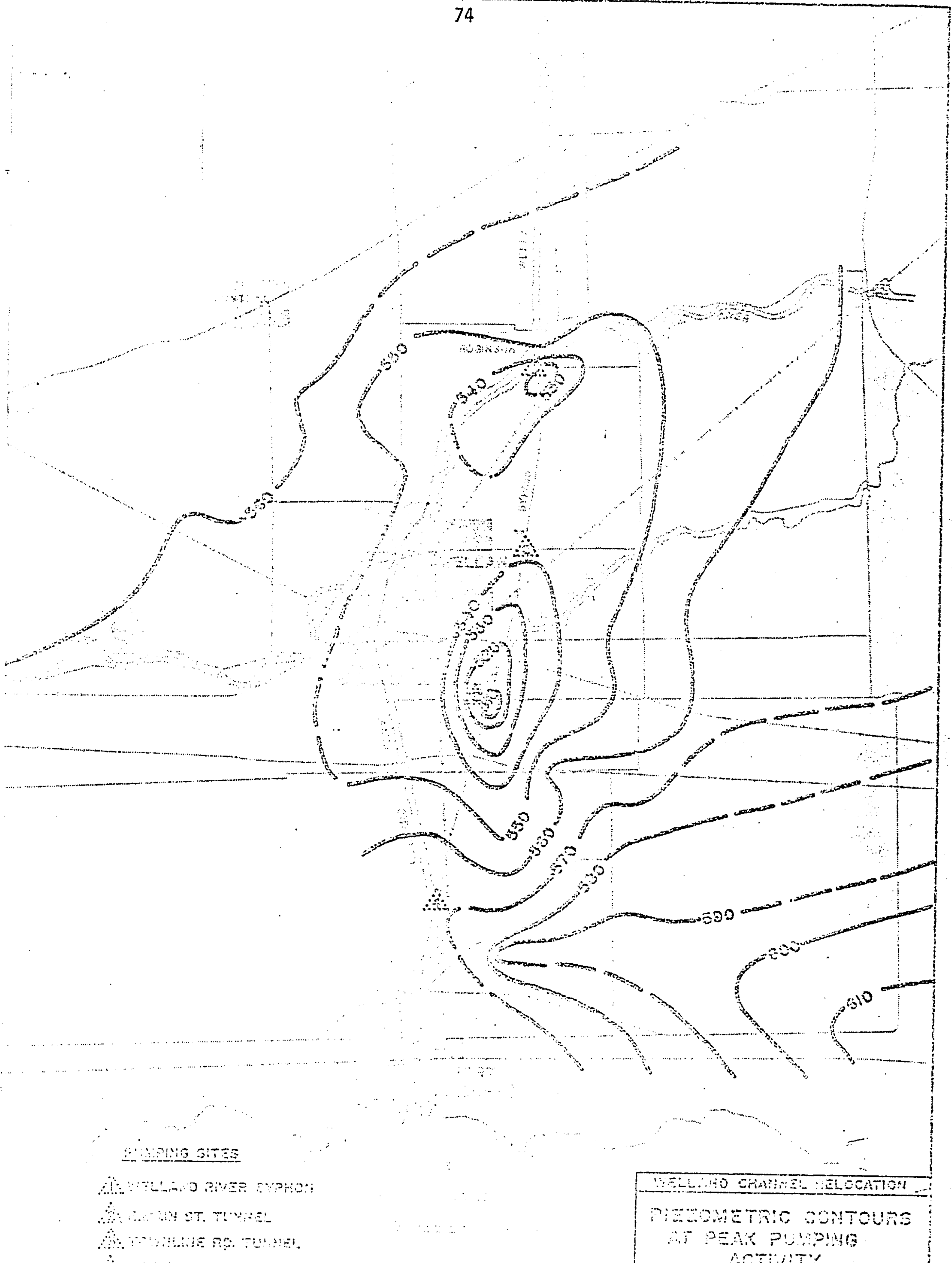


FIG-23

WELLAND CHANNEL RELOCATION

PIEZOMETRIC CONTOURS AT PEAK PUMPING ACTIVITY

JUNE 1970

The piezometric level in each successive permeable zone in the bedrock is higher than for the zone just above it, and the difference becomes larger as the depth increases. In most of the observation wells, a 1.0 foot drawdown in the upper aquifer causes about a 0.7 foot drawdown in the lower permeable zones at 80 to 100 feet in the bedrock, indicating that the lower permeable zones are hydraulically connected with the main aquifer and that the groundwater from deeper zones is moving upward.

7.4 Hydrochemistry

In order to study the preservation of the foundation rock, data collected during February and March 1970 (Table 4) is analyzed to show the variations with time of the chemical composition of the water and the individual chemical processes contributing to the changing character of the groundwater.

7.4.1 Changes in Concentration

Except for local increases in concentration of dissolved solids due to intrusion of black mineralized water from deeper zones, the hydrochemical processes occurring in the rock environment are tending to give an expression of general desalination of the main water-bearing horizon within the zone of influence of pumping. The resulting decrease in concentration on the south side of the tunnel is much less as compared to the north and northwest side, where the effect of pumping is more severe. The decrease in concentration has

TABLE 4

Chemical Analysis of Groundwater

During Construction

Date: November 1968

H. G. Acres Limited
Calgon Corporation

Well No.	No.	Ca	Mg	Na	SO_4	cl	HCO_3
Well No. 4	42	1,028	270	2,880	3,000.	4,750	157

Date: February 4, 1970

St. Lawrence Seaway Authority
and Ontario Water Resources Corp.

Well No.	No.	Ca	Mg	Na	SO_4	cl	HCO_3
AAY_1	43	3,640	984	11,000	1,810	25,300	105
AAY_3	44	576	163	725	2,070	889	172
BBY_1	45	1,040	336	4,250	2,540	7,660	78
BBY_3	46	592	173	257	1,690	474	165
cc-x	47	608	163	209	1,700	452	146
135	48	544	163	341	1,880	376	85
3,568	49	85	22	9	116	18	166
3,712	50	59	22	7	558	14	191
rv	51	128	67	20	296	46	262
NN	52	480	187	284	1,860	234	56
3,502	53	492	153	105	1,560	83	170
166	54	480	144	99	1,530	73	168
147	55	528	135	100	1,620	103	106
5	56	296	62	61	810	53	97
167	57	520	129	103	1,680	119	88
51	58	516	120	83	1,600	27	186

Table 4 - Chemical Analysis of Groundwater After Construction - 2

Well No.	No.	Ca	Mg	Na	SO_4	cl	HCO_3
50	59	528	154	238	1,770	272	87
P-47	60	312	84	113	1,000	56	125
EE-x	61	560	182	585	1,980	765	73
4052	62	560	65	29	1,270	12	164
DD-x	63	556	163	239	1,790	409	78
II	64	508	125	133	1,660	83	53
3,717	65	444	130	99	1,360	302	50
GG	66	88	38	43	158	34	350
G	67	152	43	41	200	72	189
vy_3	68	308	74	78	980	26	57
Sump	69	529	144	300	1,700	603	93
12" well	70	462	138	358	1,360	565	36
102	71	592	144	290	1,620	522	83
AA	72	516	106	15	1,000	13	341
FF-x	73	384	208	158	2,270	10	51
2,013	74	296	216	179	1,370	89	72
3,566	75	68	41	18	84	39	345
uy_3	76	1,865	566	4,780	900	7,980	114
4,137	77	60	22	10	130	5	190
4,225	incomplete						

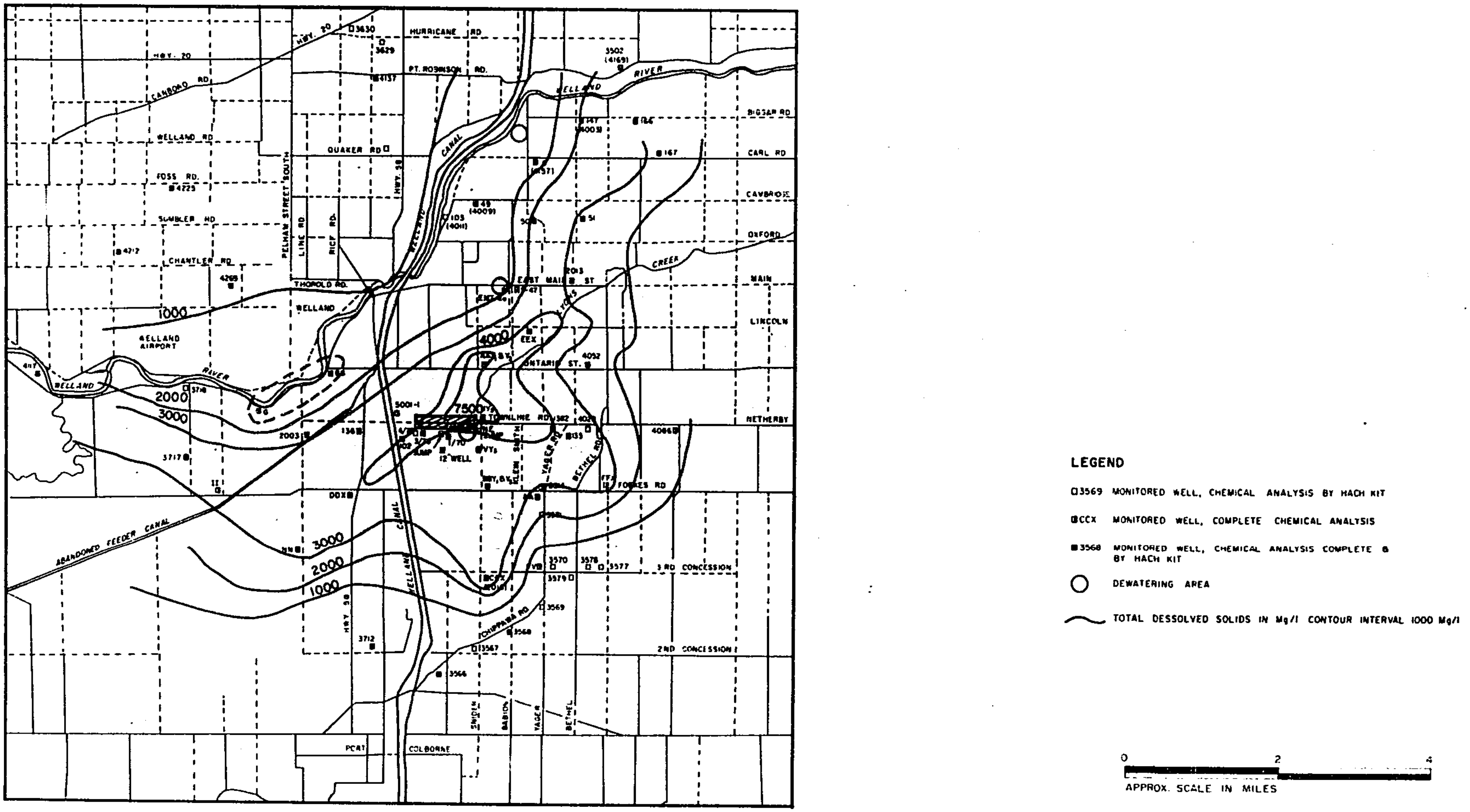
Table 4 - Chemical Analysis of Groundwater After Construction - 3

Well No.	No.	Ca	Mg	Na	SO4	cl	HCO_3
4,269	78	147	38	31	127	32	187
4,117	79	544	135	143	1,620	225	69
4,212	80	56	15	24	127	2	116
49	81	268	60	67	650	60	152
136	82	492	142	139	1,780	86	79
4,086	83	328	32	13	740	20	103

occurred quite rapidly in areas where heavy pumping is done close to the previously established boundary of saturation. The range of total dissolved solids varies from 320 mg/l in recharge areas to 3,970 mg/l around the tunnel site where highly mineralized water from depth has intruded the main aquifer; the concentration of dissolved solids ranges from 4,640 mg/l to 5,180 mg/l. In deeper zones the concentration rises to as much as 49,300 mg/l. The variations in the amount of total dissolved solids in the main aquifer is shown in Figure 24.

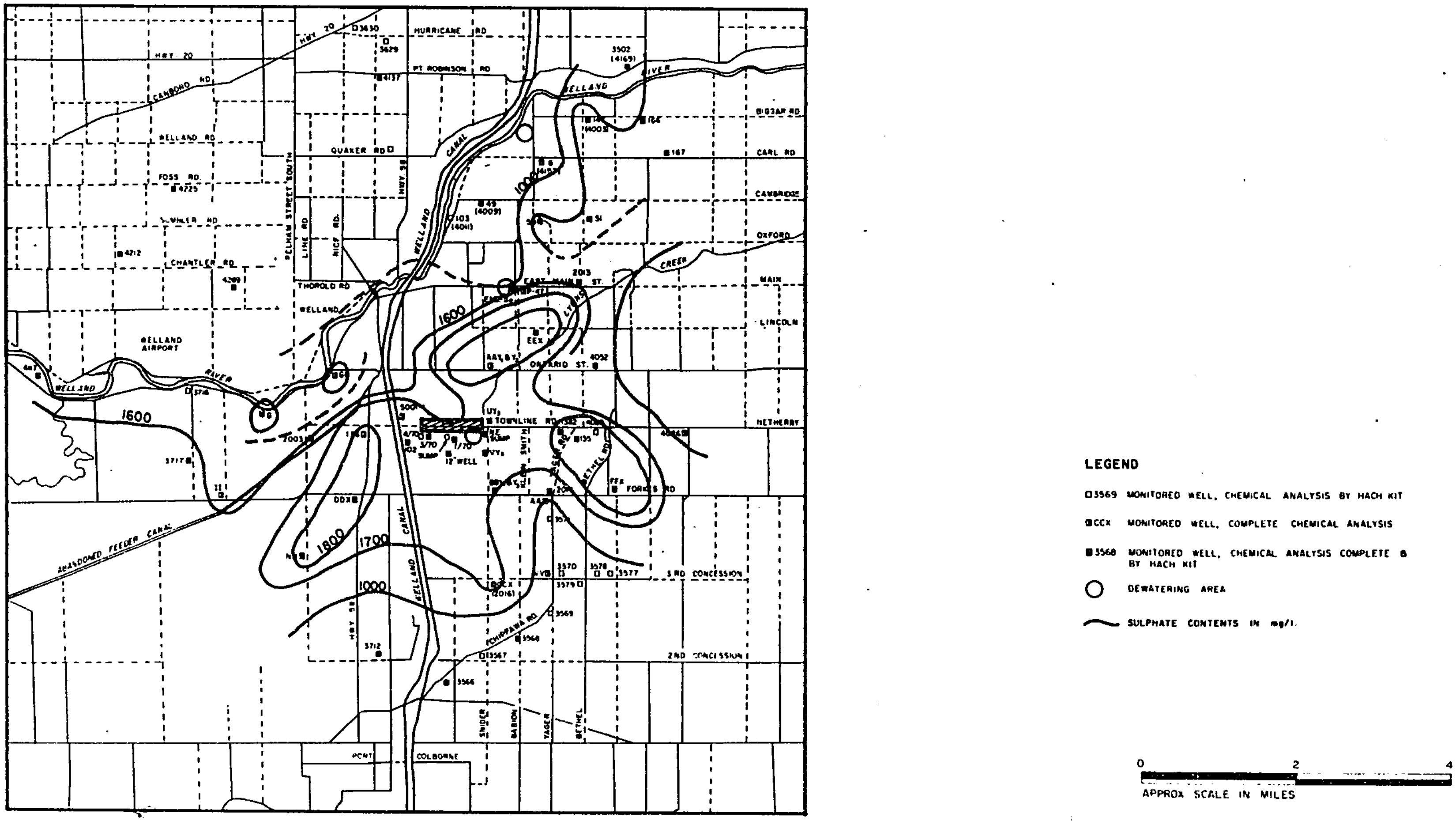
7.5 Changes in Individual Ion Concentration

The sulphate content of the groundwater, ranging from 100 mg/l to 1,700 mg/l, also shows a relative decrease in range, particularly in the central area of the Welland region. On the south side of the tunnel where the influence of pumping is minimal, increase in sulphate content is rapid over a short distance as compared to the northwest direction where the rate of flow is higher (Figure 25). The increase in chloride content of the groundwater is associated with the lowering of the piezometric level in the main aquifer which resulted in an upward leakage of black mineralized water in a zone of greater head differential. The chloride concentration within the zone where drawdown is more than 15 feet, varies from 200 to 900 mg/l and increases to 25,300 mg/l in the deeper zones. The average Na:Cl ratio in brine from deeper zones is about 0.85 which is the same as found in normal sea water. The boreholes affected by the leakage from depth, generally have a Na:Cl ratio less than unity.



CONCENTRATION OF TOTAL DISSOLVED SOLIDS DURING CONSTRUCTION

FIG 24



CONCENTRATION OF SULPHATE CONTENTS DURING CONCENTRATION TIME

FIG 25

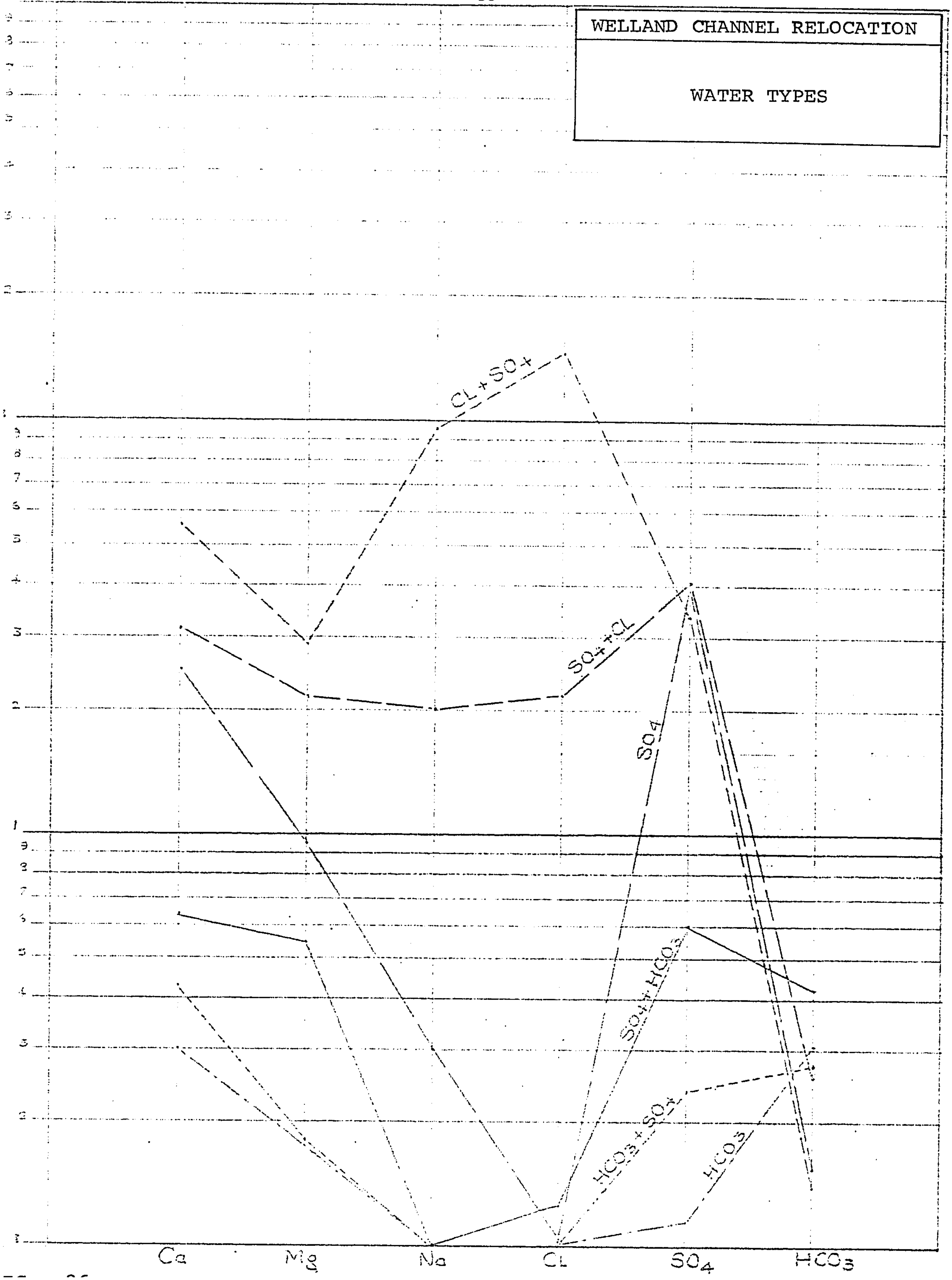
7.6 Chemical Zonation

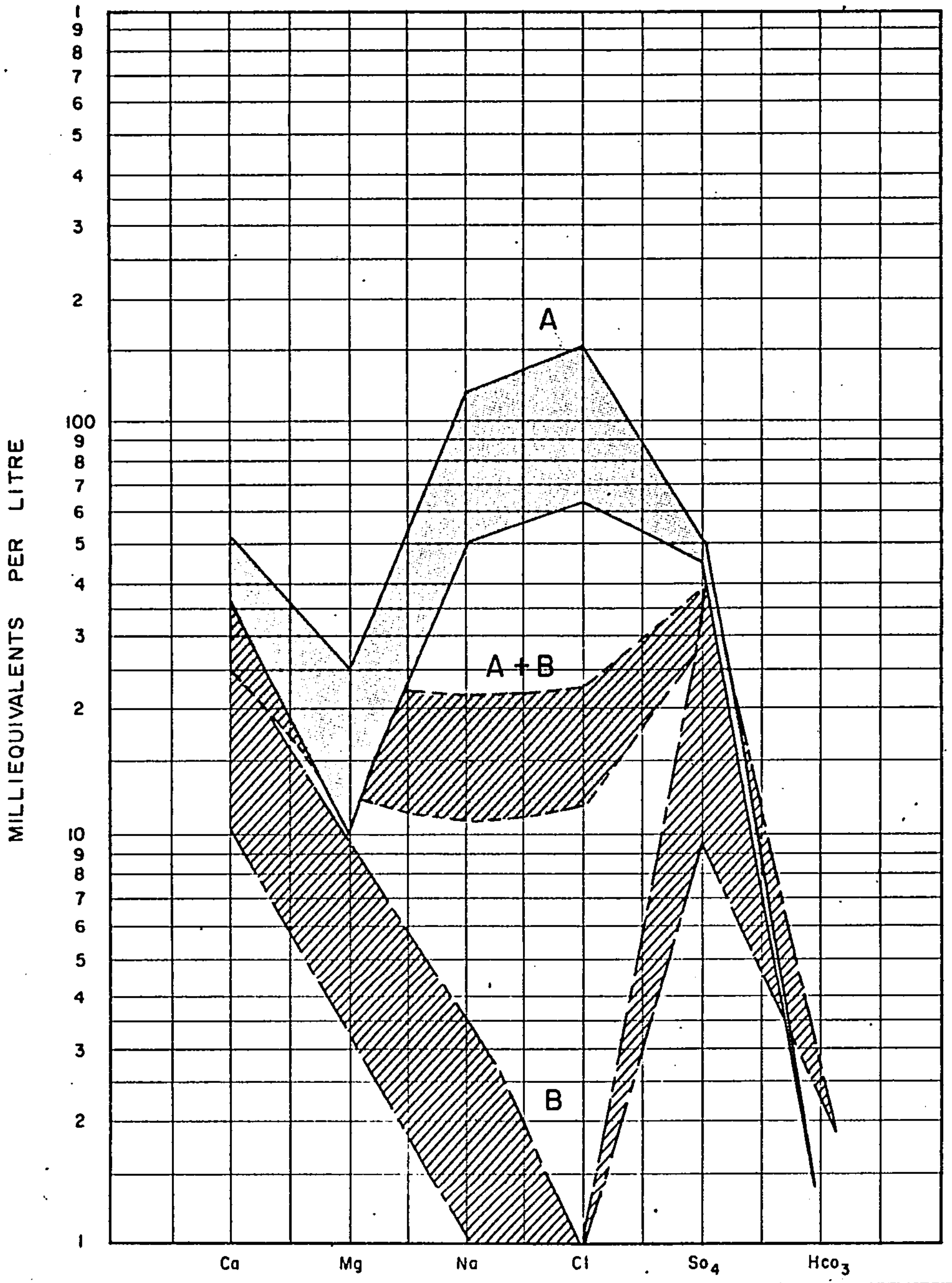
On the basis of changes in the chemical composition, the groundwater can be separated into two groups, each representative of a different horizon. The first group represents water in the main aquifer with Ca and SO_4 as predominant ions and mineralization less than 3,400 mg/l. The second group is represented by black mineralized water which occurs below the fresh water body. Where the fresh water horizon is contaminated by the leakage of brine from depth, a mixture of both groups is found (See Appendix I), and mineralization of the mixture ranges from 3,400 mg/l to 5,200 mg/l, depending upon the percentage of the contaminant present. The different groups and water types are shown in Figures 26 and 27.

7.6.1 Horizontal Zonation

The change in flow conditions has introduced a change in the chemical zonation of the groundwater in the main water-bearing horizon. The primary water of $HCO_3 + SO_4$ and $SO_4 + HCO_3$ type with mineralization of less than 1,000 mg/l has invaded a vast area especially on the northwest side of the Townline Tunnel.

The $Cl + SO_4$ type water which occurred in a small area near the tunnel site, under the natural flow conditions, has been flushed out and $SO_4 + Cl$ type mixed water has extended into a wider area all around the tunnel site (Figure 28). The area occupied by SO_4 type water has narrowed down considerably on the north and west side of the tunnel, due to the extension in the zone of aggressive primary water. Within the zone of influence of pumping, the groundwater shows a lesser increase in mineralization for shorter distance and time as


WELLAND CHANNEL RELOCATION
WATER TYPES
CL+SO4
SO4+CL
SO4
SO4+HCO3
HCO3+SO4
HCO3
Ca
Mg
Na
CL
SO4
HCO3
1
2
3
4
5
6
7
8
9



LEGEND

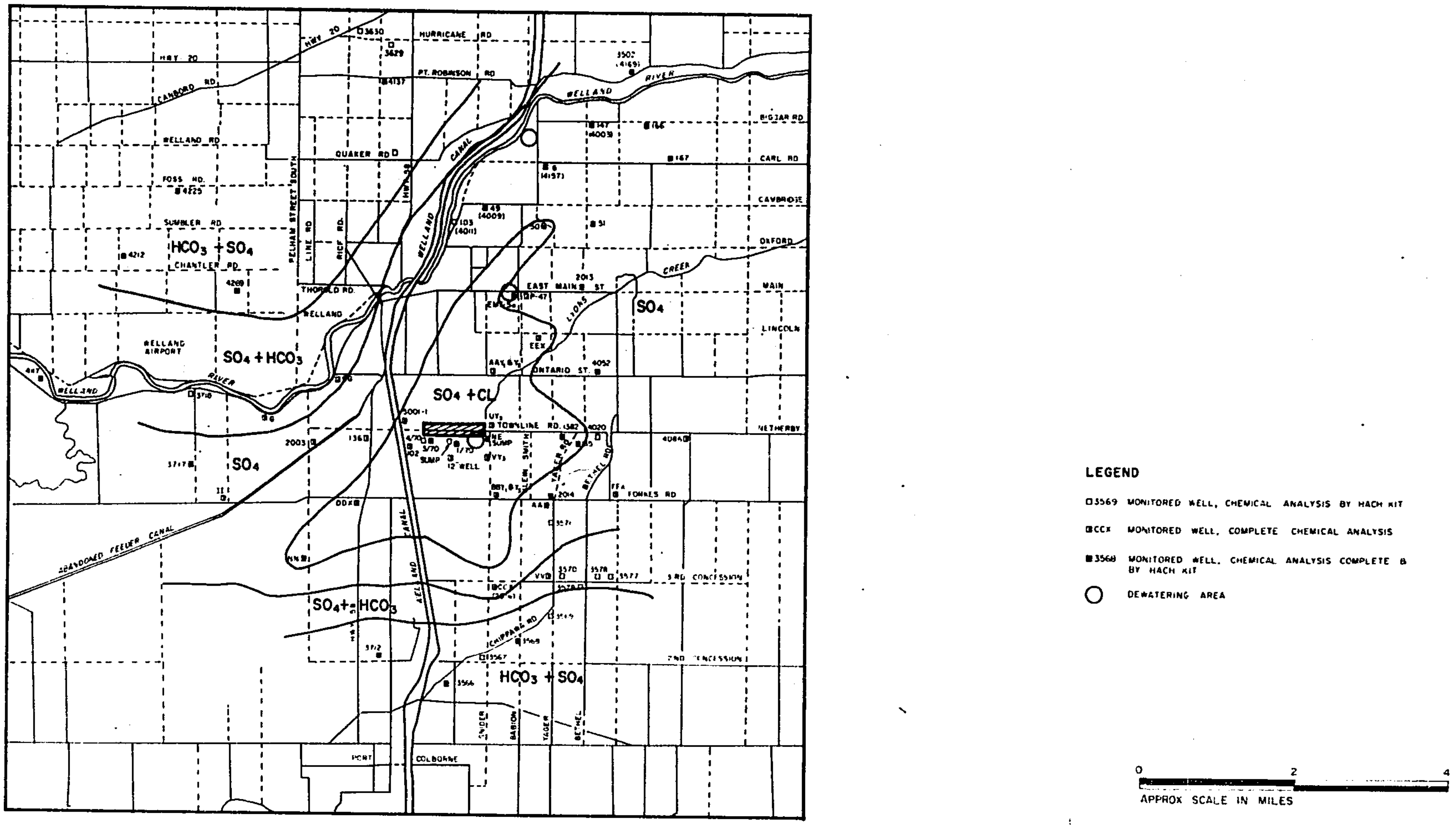
A = NACL TYPE BRINE FROM DEEPER ZONES

B = SO_4 DOMINANT WATER FROM MAIN AQUIFER

A+B = MIXTURE OF BOTH TYPES

DIFFERENT GROUPS OF WATER

FIG-27



CHEMICAL ZONATION
OF GROUNDWATER
DURING CONSTRUCTION

FIG-28

compared to the preconstruction conditions, due to a steeper gradient.

The migration of black mineralized water from depth was a local occurrence at the tunnel site prior to the construction dewatering, but after the lowering of the piezometric surface in the main aquifer, the upward leakage has increased significantly, especially within the area occupied by SO_4 + Cl type water. The increase in Na and Cl content of the groundwater is more predominant on the south side of the tunnel. The slow and continuous movement of groundwater through the rock interstices prior to construction dewatering provided sufficient time of contact for groundwater to take more mineral matter into solution. But, by providing a nearby outlet, this mineralized water is discharged rapidly and at the same time less mineralized water has moved in to take its place.

7.6.2 Vertical Zonation

The mineralization of the groundwater increases with increasing depth. Predominantly Cl type water occurs in zones of deeper circulation, whereas concentration of total dissolved solids generally exceeds 15,000 mg/l and increases to as much as 50,000 mg/l with increase in depth. The concentration of Ca does not exceed 600 mg/l in the main fresh water aquifer, but in the lower horizons it is close to one-half of the Na concentration. The chloride content increases with increase in total dissolved solids, ranging from 20 percent of chloride for 10,000 mg/l of total dissolved solids to 60 percent for 40,000 TDS. However, the SO_4 concentration tends to decrease with depth, due to the reduction of sulphate in the deeper zones.

7.7 Application to Conditions Following Construction

The activities of individual ions and the ionic strength of each sample were computed by the method described earlier. The results of the calculations are shown in Table 5. The ionic strength of water samples from the main aquifer range from .007 to 0.1 and from .24 to .89 in samples from deeper zones. The concentration of NaCl in groundwater from the main aquifer is generally less than 0.05 moles per liter, therefore the ionic product of Ca and SO_4 at saturation is between 1.99×10^{-4} and 2.8×10^{-4} except in the case of water samples from deeper zones where the values of ionic product range from 4.3×10^{-4} to 8.0×10^{-4} due to concentration of NaCl in the range of 0.2 moles per liter.

The results of the present calculations are plotted on the previously obtained curves (i.e., $CaSO_4$ vs U and $CaSO_4$ vs NaCl) showing the solubility relationship (Figure 29 and Figure 30) for waters of different ionic strength. The data from both sets of analyses (i.e. prior to construction and during the construction) follows a similar pattern and confirms the values of solubility obtained earlier for different ranges of concentrations.

The values of K_{iap} are compared with the equilibrium constant K_{gyp} and where the values of K_{iap} are less than K_{gyp}, the deficit in saturation (Table 6) is calculated and the results are projected on the map of the study area.

TABLE 5

Well No.	Ionic Strength	$(Ca)(SO_4)$ mole/liter	Coefficient of Activity	Kiap
42	0.2668034E-00	0.8002354E-03	0.2692263E-00	0.5800326E-04
43	0.8970475E-00	0.1709556E-02	0.2459723E-00	0.1034321E-03
44	0.1149166E-00	0.3093826E-03	0.3493888E-00	0.3776709E-04
45	0.3334432E-00	0.6854415E-03	0.2547065E-00	0.4446827E-04
46.	0.9254551E-01	0.2596041E-03	0.3749266E-00	0.3649252E-04
47	0.9121960E-01	0.2681979E-03	0.3766826E-00	0.3805454E-04
48	0.9306949E-01	0.2653750E-03	0.3742414E-00	0.3716750E-04
49	0.1027349E-01	0.2558459E-05	0.6629623E-00	0.1124495E-05
50	0.7874664E-02	0.8879389E-06	0.6940901E-00	0.4277744E-06
51	0.2128475E-01	0.9831169E-05	0.5699631E-00	0.3193732E-05
52	0.8795404E-01	0.2316634E-03	0.3811456E-00	0.3365420E-04
53	0.7442856E-01	0.1991558E-03	0.4020518E-00	0.3219266E-04
54	0.7217777E-01	0.1905619E-03	0.4059719E-00	0.3140709E-04
55	0.7564145E-01	0.2219485E-03	0.3999968E-00	0.3551118E-04
56	0.3958619E-01	0.6221281E-04	0.4858158E-00	0.1468328E-04
57	0.7614017E-01	0.2266814E-03	0.3991631E-00	0.3611740E-04
58	0.7260728E-01	0.2142264E-03	0.4052129E-00	0.3517541E-04
59	0.8555269E-01	0.2424994E-03	0.3845604E-00	0.3586242E-04
60	0.4754865E-01	0.8095763E-04	0.4609901E-00	0.1720445E-04
61	0.1082040E-00	0.2877109E-03	0.3563284E-00	0.3653062E-04

Table 5 - 2

Well No.	Ionic Strength	$(Ca)(SO_4)$ mole/liter	Coefficient of Activity	Kiap
63	0.8998579E-01	0.2582443E-03	0.3783450E-00	0.3696636E-04
64	0.7465440E-01	0.2188140E-03	0.4016659E-00	0.3530245E-04
65	0.6795585E-01	0.1566842E-03	0.4137276E-00	0.2681970E-04
66	0.1508561E-01	0.3607804E-05	0.6151204E-00	0.1365095E-05
67	0.1873691E-01	0.7888183E-05	0.5868913E-00	0.2717016E-05
68	0.4436913E-01	0.7832130E-04	0.4703365E-00	0.1732595E-04
69	0.9253263E-01	0.2611401E-03	0.3749434E-00	0.3671173E-04
70	0.7873881E-01	0.1630362E-03	0.3949229E-00	0.2542778E-04
71	0.8942711E-01	0.2488513E-03	0.3791075E-00	0.3576551E-04
72	0.5856982E-01	0.1338915E-03	0.4331602E-00	0.2512174E-04
73	0.8747882E-01	0.2261832E-03	0.3818123E-00	0.3297311E-04
74	0.6676829E-01	0.1052241E-03	0.4160108E-00	0.1821060E-04
75	0.1228090E-01	0.1482147E-05	0.6411244E-00	0.6092225E-06
76	0.3757484E-00	0.4355363E-03	0.2483796E-00	0.2686930E-04
77	0.9352319E-02	0.2023941E-05	0.6741595E-00	0.9198630E-06
78	0.1575992E-01	0.4844227E-05	0.6094883E-00	0.1799513E-05
79	0.7870984E-01	0.2286742E-03	0.3949690E-00	0.3567329E-04
80	0.8170411E-02	0.1845419E-05	0.6898809E-00	0.8783008E-06
81	0.3537643E-01	0.4520133E-04	0.5011294E-00	0.1135144E-04
82	0.7813603E001	0.2272419E-03	0.3958912E-00	0.3561558E-04
83	0.3579968E-01	0.6298086E-04	0.4995083E-00	0.1571425E-04

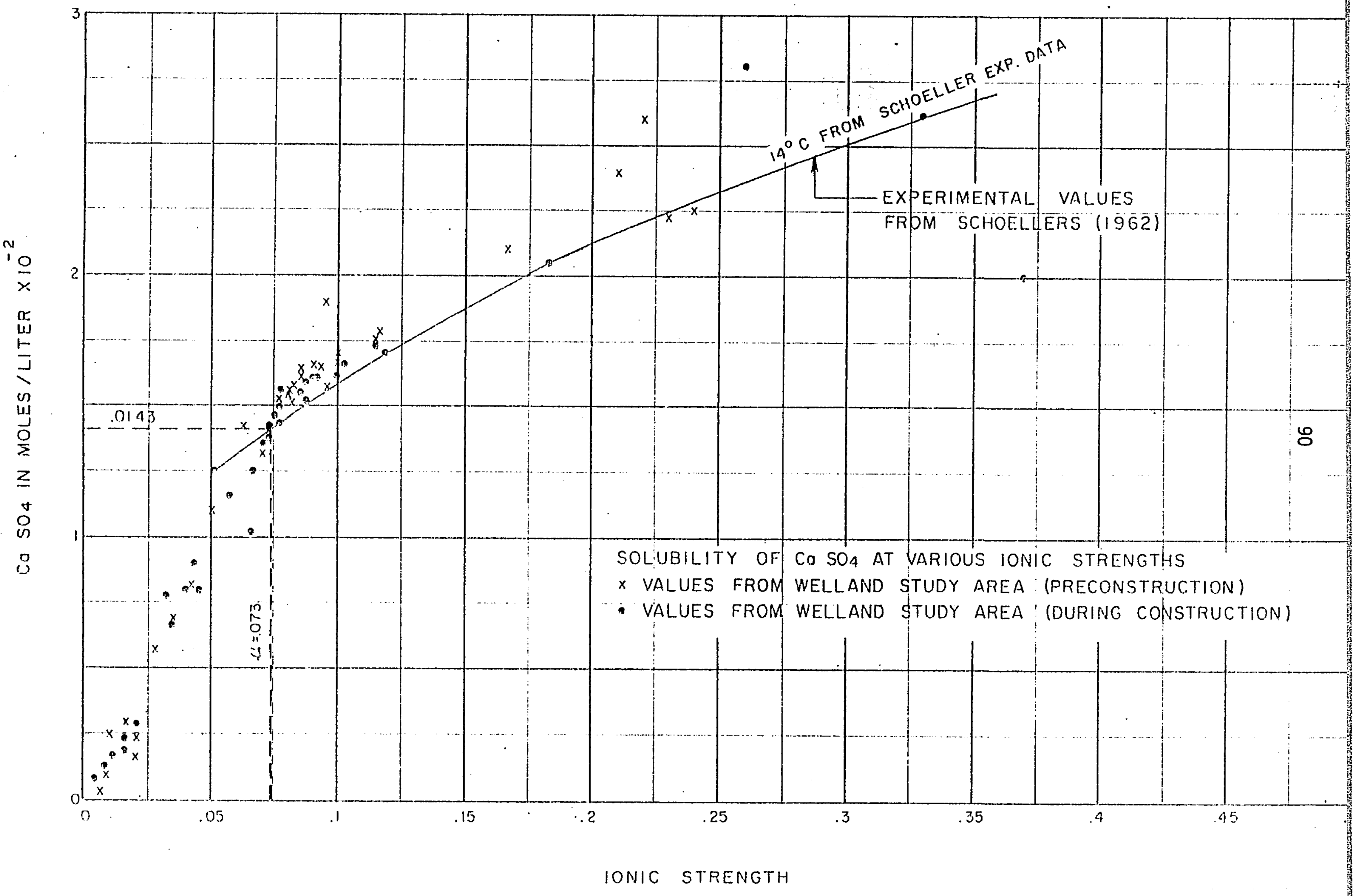

14° C FROM SCHOELLER EXP. DATA
EXPERIMENTAL VALUES FROM SCHOELLERS (1962)
SOLUBILITY OF Ca SO4 AT VARIOUS IONIC STRENGTHS
x VALUES FROM WELLAND STUDY AREA (PRECONSTRUCTION)
• VALUES FROM WELLAND STUDY AREA (DURING CONSTRUCTION)
.0143
μ=.073
Ca SO4 IN MOLES/LITER X10⁻²
0
1
2
3
0
.05
.1
.15
.2
.25
.3
.35
.4
.45
IONIC STRENGTH

FIG-29

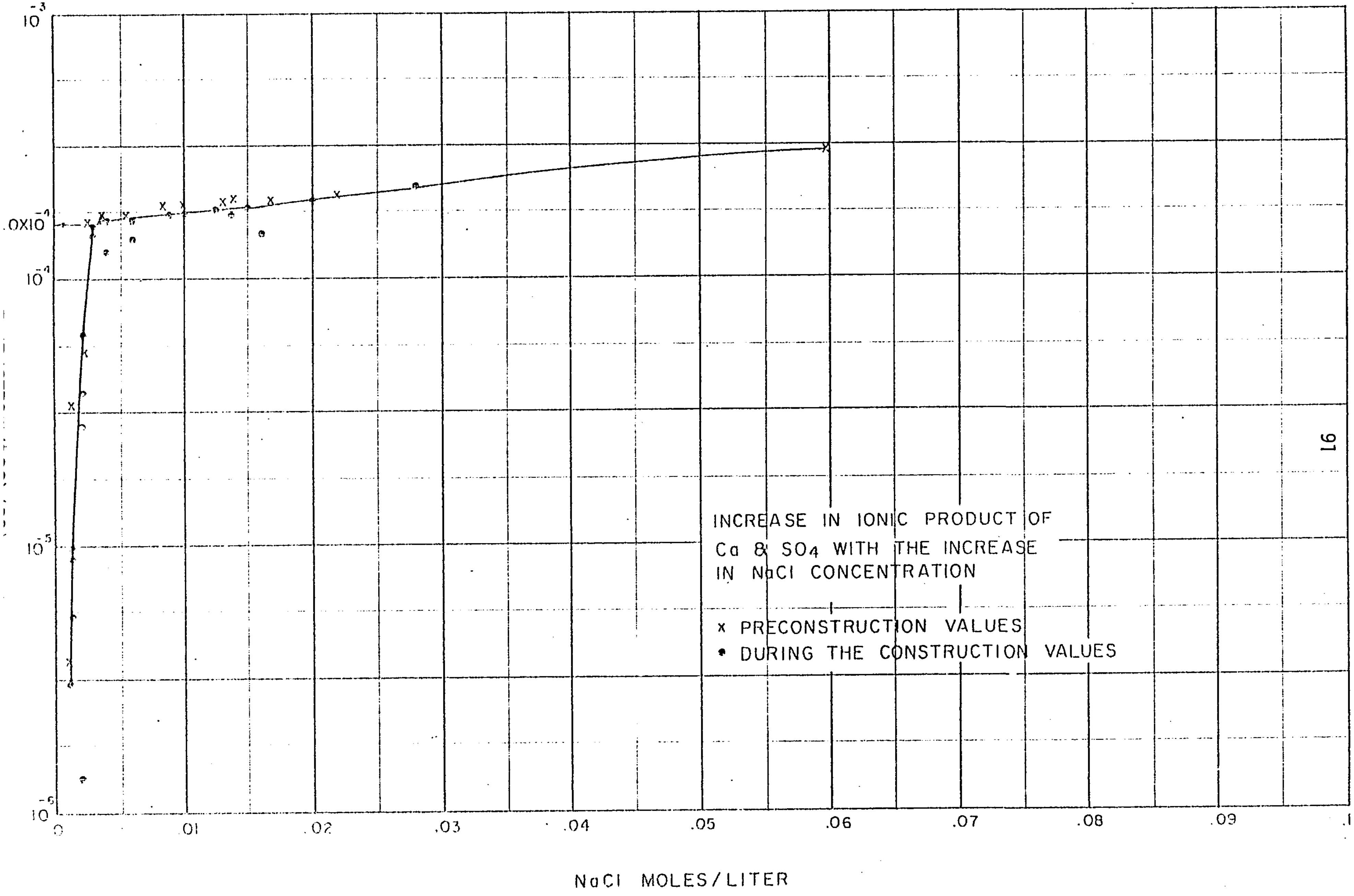

INCREASE IN IONIC PRODUCT OF
Ca & SO_4 WITH THE INCREASE
IN NaCl CONCENTRATION
x PRECONSTRUCTION VALUES
● DURING THE CONSTRUCTION VALUES
10^{-3}
.0X10^{-4}
10^{-4}
10^{-5}
10^{-6}
0
.01
.02
.03
.04
.05
.06
.07
.08
.09
.1
NaCl MOLES/LITER

FIG-30

TABLE 6

Deficit in $CaSO_4$ Saturation

Well No.	Deficit in Saturation mole/liter	Deficit in Saturation mg/l
49	0.7280686E-04	1690
50	0.6642294E-04	1760
51	0.9850459E-04	1470
54	0.1941592E-03	41
56	0.1355835E-03	845
60	0.1505798E-03	690
65	0.1869480E-03	213
66	0.8457260E-04	1650
67	0.9290404E-04	1500
68	0.1446547E-03	709
70	0.2051754E-03	182
72	0.1705505E-03	340
74	0.1849017E-03	500
75	0.7785119E-04	1740
76	0.5187020E-03	625
77	0.7040842E-04	1710
78	0.8614283E-04	1545
80	0.6723596E-04	1722
81	0.1274237E-03	990
83	0.1282521E-03	839

7.8 General Discussion

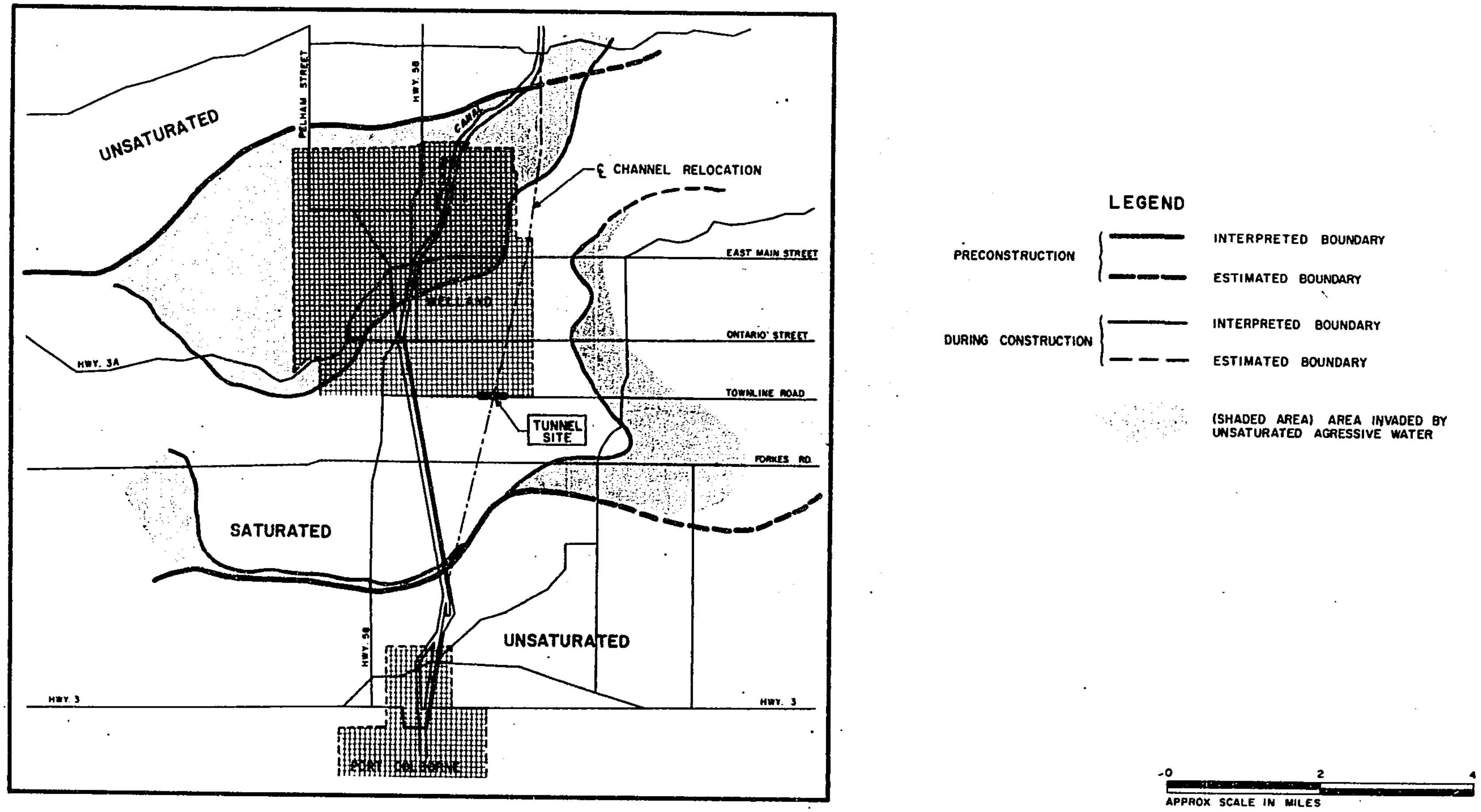
The initial investigation of the natural hydrogeological conditions was primarily directed to establish a suitable method to study the solution of gypsum in a particular hydrogeological environment. However, it left a number of unanswered questions regarding the changes which might take place due to the continuous withdrawal of groundwater from the construction sites. The object of this second study under the altered flow conditions was to find some reasonable answers to the following questions:

1. What effect continuous pumping for dewatering purposes or permanent depressurization of the aquifer would have on the chemical composition of the groundwater?
2. Would the chemical equilibrium between gypsum and water be disturbed? If it did, to what extent?
3. What would be the rate and direction of the movement of the saturation boundary?
4. What other factors (if there are any) would accelerate the movement of the saturation boundary?
5. In case a segment of the boundary becomes dangerously close to the tunnel site, what economical methods can be postulated to control its movement?

The change in flow conditions, due to pumping for dewatering, has induced a considerable change in the chemical composition of the groundwater. The changes in concentrations and chemical zonation of the groundwater have been discussed in detail in the previous sections. The effects of these changes on the solubility of gypsum can be deduced logically.

It appears from the observations that the higher the rate of withdrawal of groundwater or the steeper the hydraulic gradient, the lower the total dissolved solids. In other words, an increase in the rate of flow of groundwater decreases the time of contact between gypsum and groundwater. Since the time of contact between the mineral and groundwater is related to the length of flow path, under the altered physical conditions, groundwater would require a longer flow path to compensate for the increase in velocity, in order to obtain the saturation level. Hence, the saturation boundary would tend to migrate towards the pumping centers (Figure 31).

This logical conclusion is confirmed by the solubility calculations. The calculations of the activity product constant indicate that the pumping from the Welland River syphon and the Townline Road Tunnel has disturbed the physicochemical equilibrium which existed prior to the construction dewatering. As a result, the boundary between saturated and unsaturated water with respect to gypsum has moved considerably in the northwest direction, towards the city of Welland (Figure 32). A significant migration has also taken place on the southeast side of the tunnel. The movement of the boundary on the south side of the tunnel, however, is much less as compared to the north and northwest side where the effect of pumping is more severe.



MOVEMENT OF
SATURATION BOUNDARY

FIG-31

NOTE: GROUNDWATER BETWEEN PAIRS
OF BOUNDARIES IS SATURATED
WITH RESPECT TO GYPSUM;
THAT OUTSIDE IS NOT SATURATED.

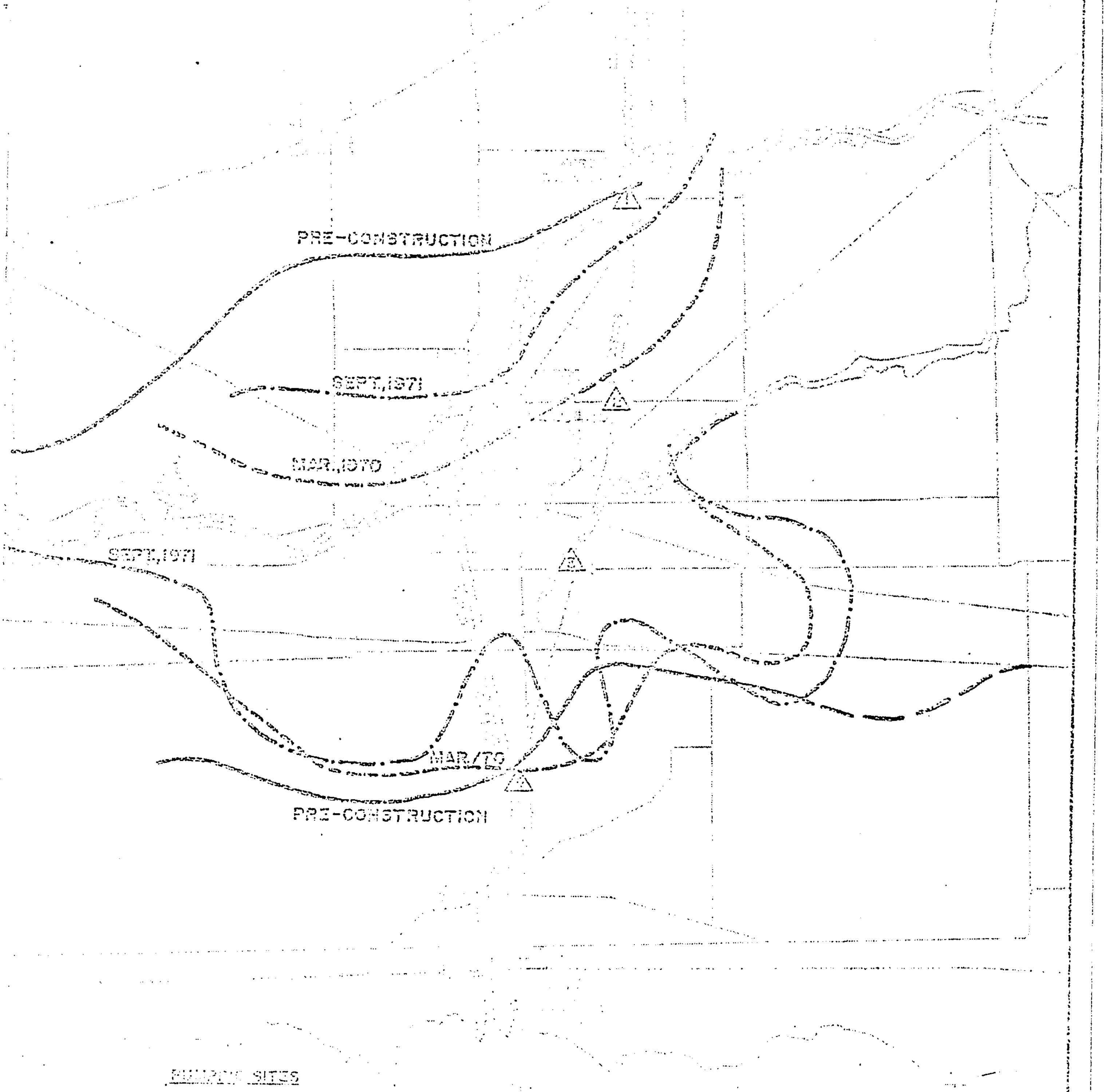


FIG-32

WELLAND CHANNEL RELOCATION

SATURATION BOUNDARIES
GYPSUM-SATURATED
GROUNDWATER
PRIOR TO CONSTRUCTION, 1970 & 1971
(FROM ACRT. DATA)

It appears from the present study that as soon as the cone of depression approaches or overrides the saturation boundary it starts moving towards the pumping centre. The greater the drawdown near the boundary the greater the movement; therefore, the location of the dewatering system is quite critical in bringing about the undesirable changes in groundwater chemistry (See Appendix I). The location of the Welland River syphon being closer to the northwest recharge area and previously established saturation boundary has resulted in an appreciable demineralization of the groundwater. Aggressive groundwater with mineralization less than 1,500 mg/l has invaded a vast area on the southeast side of the Fonthill, towards Port Robinson and the old Welland Canal. The interference from the Townline Tunnel pumping has caused a further extension of the front of aggressive water on the south side of Fonthill.

At present it is difficult to estimate the rate of movement of the saturation boundary, due to irregularity in the rate of pumping from various construction sites. However, when permanent dewatering systems at the Townline Tunnel and at the East Main Street Tunnel start functioning and an equilibrium between recharge and discharge is reached, it would be possible to determine the position of the stabilized boundary and its response to variations in pumping rates, by conducting similar studies at different intervals.

Although the zone of saturated water has been reduced due to the migration of the saturation boundary in the direction of pumping centres, the groundwater at the Townline Tunnel site is still in a state of equilibrium with gypsum deposits (Figure 30).

Though at present groundwater at the tunnel site is saturated with respect to calcium sulphate and solutioning at the tunnel area is not active, nevertheless it is possible that at some distant future during the life of the structure, a segment of the boundary may approach very close to the tunnel site. In the design considerations it is recommended that under such conditions a wall of concrete or a grout curtain should be constructed around the foundation of the tunnel to cut off the flow of the aggressive water beneath the foundation. However, there is another economical solution which is being postulated on the basis of these studies. To restrict the advance of aggressive water, the saturated water being pumped from the permanent dewatering system at the tunnel site could be recirculated. This can be achieved by drilling recharge wells near the approaching front of aggressive water. The saturated water when pumped in from recharge wells, would create a dome of saturated water which would restrict the further movement of the aggressive front.

CHAPTER VIII

SUMMARY AND CONCLUSION

8.1 Summary

In Townline Tunnel area where gypsum-bearing rocks are present, the possibility of gypsum solution by groundwater both under natural and under altered hydrogeological conditions was investigated. The hydrogeological environments and the chemical processes taking place in it were assessed by studying the solid phase, liquid phase and interaction between the two. The solid phase included the topography and geology of the area and occurrence and distribution of gypsum. The liquid phase involved investigation of occurrence, movement and chemical character of groundwater. Leaching of gypsum which is a process of the interaction of rock and groundwater was evaluated by methods of chemical thermodynamics for the gypsum-water system by studying sulphate-calcium equilibrium in the liquid phase. The degree of aggressiveness of the groundwater was determined and zones of active solution were delineated. The results obtained from the chemical equilibrium study were projected on the map of the study area to determine the approximate position of the boundaries between unsaturated and saturated water with respect to gypsum. The monitoring wells were installed near the potentially mobile boundaries. The changes produced by dewatering at construction site were recorded, and assessment of the future trends and changes was made.

8.2 Conclusions

(1) The rate of solution depends on many factors. Some of the important factors include the lithological character of the parent material, its permeability, its relation to sources and kind of liquid, the rate of circulation of liquid, the time in which the liquid is in contact with the soluble material and the volume and the concentration of chemical constituents in the liquid.

(2) The problem was investigated by studying the hydrogeologic environments, which included the topography and geology of the area, occurrence and distribution of soluble material and occurrence, movement and chemical character of the groundwater. The leaching process which results from interaction of gypsum and groundwater was investigated by studying the sulphate-calcium equilibrium in the liquid phase.

(3) To assess the possibility of the solution of gypsum, it is important to study in detail the chemical character of the solvent which comes into contact with the soluble material. The knowledge of variations in the total and individual ion concentration, progressive changes in the chemical type of water and the extent of area occupied by each type, is essential to minimize the possibility of erroneous interpretation and to analyze the future changes in chemical composition of groundwater which may take place due to alterations in the flow conditions.

(4) The possibility of dissolution and the magnitude of its occurrence can be determined by studying the physicochemical equilibrium between the gypsum and the aqueous solution in contact with it.

(5) In order to establish a reasonable value of the equilibrium constant, the conclusions drawn from both the theoretical analysis and the analysis of the field data should be considered together.

(6) To establish the feasibility of the project or to monitor the future changes in hydrochemical processes, it is essential to determine the approximate position of the boundary between saturated and unsaturated aggressive water.

(7) The object of monitoring wells should be to determine the rate of intrusion of unsaturated water toward the foundation of the structure.

(8) The change in the groundwater regime due to the withdrawal of groundwater induces a relative change in the mineralization of the groundwater. As soon as the cone of depression approaches or overrides the saturation boundary, it starts moving towards the pumping centre. The greater the drawdown near the boundary, the greater the movement; therefore, the location of the dewatering system is quite critical in causing changes in groundwater chemistry.

(9) On the basis of this study, it was concluded that the groundwater at the Townline Road area is saturated with calcium sulphate and the tunnel structure can be founded on the gypsiferous dolomite without any expensive design changes. However the boundary between saturated and unsaturated water should be monitored until the position of the boundary is stabilized.

8.3 Recommendations

(1) Future development in the Welland region may put additional stress on the squifer, therefore it is recommended that a study should be carried out to determine the rate of movement of the saturation boundary as related to the rate of pumping.

(2) In the south plug area of unsaturated water, the rate of pumping increased from 1,000 I.G.P.M. to 12,000 I.G.P.M., within less than 2 years, due to the solution of gypsum. It is therefore essential that groundwater chemistry should be monitored continuously at least until the boundary of saturated water is stabilized.

(3) Further research is required to understand the causes of supersaturation in groundwater and to determine the factors which control the precipitation of minerals in a hydrogeological environment.

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APPENDIX I

APPENDIX I

Principles of Hydrochemistry and Their Application to Study of Groundwater Movement

INTRODUCTION

The importance of hydrochemistry in studying the water quality and weathering processes such as formation of clay minerals (Harriss 1966), solution of limestone (Back 1963), development of caverns, solution channels and Karstic erosion (Swinnerton 1932, Harrick and Legrand 1964), was realized a long time ago. Recent advances have clearly demonstrated the usefulness of hydrochemistry in the field of agriculture (Hem 1966), oil exploration (Sukharev 1951, Chilingen 1955, Scholler 1956), salt water contamination (Burdon and Dounax 1967, Jhons 1968), groundwater and surface water pollution, deterioration of concrete (Laptev 1939), steel corrosion and incrustation and land subsidence (Olive 1957, Klein 1962). In the field of geotechnical engineering the principles of hydrochemistry are being used to study the preservation of soluble foundation rock beneath the dam (Memenko 1960) tunnel and hydraulic structures. The relationship of physical flow and chemical character of groundwater is widely used in hydrology for studying the nature and extent of flow systems, direction of groundwater movement, location of discharge and recharge areas, and in determining the type and origin of contamination.

The purpose of this paper is to discuss the application of some of the frequently used geochemical principles to determine the direction of groundwater movement in a particular hydrogeological environment. The emphasis will be placed on the anomalies which might lead to misinterpretation when parameters such as the concentrations of dissolved solids and individual ions, changes in chemical composition, and physicochemical equilibrium are used as bases for determining the groundwater movement. The utility of the above methods and the anomalies involved are discussed in the light of the studies made in the Welland area.

The Federal Government initiated a major construction project to improve the alignment of the Welland Canal. In the vicinity of the City of Welland, two vehicular crossings (Townline Rail/Road Tunnel and Main Street Roadway Tunnel) beneath the canal were constructed recently.

The observations on which this paper is based were made as part of the investigations of groundwater conditions in the Welland region by the St. Lawrence Seaway Authority and H.G. Acres Limited. As the discussion of the geochemical principles is followed by the example of Welland area, a brief description of hydrogeology of the Welland region is included in this paper.

HYDROGEOLOGY

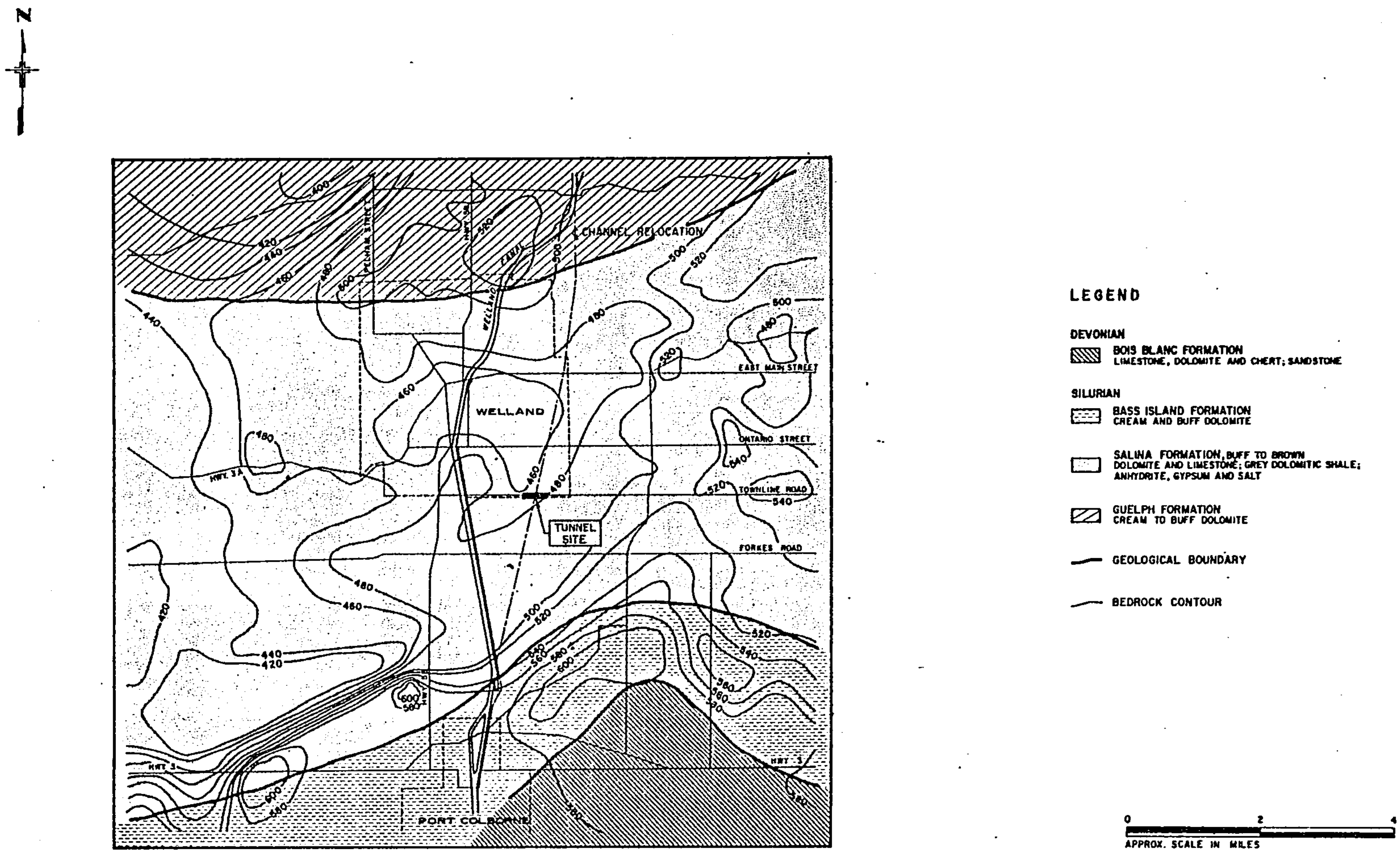
The Niagara peninsula, south of Niagara escarpment, is underlain by Paleozoic sedimentary strata of Silurian and Devonian age. Both tunnels are located in the area underlain by Salina formation, which occupies a position between Guelph and Bass Island formations as shown in Figure (1). The strata dip south at an inclination of about 30 feet/mile.

In the Welland area the bedrock comprises dolomite and shaly dolomite with layers and inclusions of gypsum. Onodaga escarpment in the area north of Port Colborne is a dominant feature of the bedrock topography. To the south of the escarpment minor outcrops occur and bedrock elevation ranges from 590 to 600 feet.

Pleistocene deposits comprising till, sand and gravel and stratified deposits of clay and silt, ranging in thickness from 60 to 150 feet overlie the bedrock.

GROUNDWATER

Groundwater in the Welland area occurs within the upper 5 to 15 feet of the fractured and weathered bedrock. Pleistocene deposits that overlie the bedrock are practically impervious except for the local pervious zones at the overburden/bedrock contact. The aquifer is under confined artesian conditions and the movement of groundwater is controlled by



BEDROCK TOPOGRAPHY
AND GEOLOGY

FIG-1

fracture permeability. A highly mineralized NaCl type brine occurs at deeper zones.

The areas of recharge (i.e. Port Colborne and Fonthill) are identified by piezometric highs and HCO_3 type water which are coincident with local topographic highs. Groundwater from Port Colborne and Fonthill areas moves towards Welland River.

TOTAL DISSOLVED SOLIDS

The primary controls on total dissolved solids are the original chemical character of water, the distribution and solubility of minerals, the permeability of the material and the length of the flow path. The chemistry of the natural water is very complex and there are a number of factors and processes which influence the concentration of dissolved solids in a particular hydrogeological environment. The concentration due to dissolution alone depends primarily on temperature, pressure, time and surface area of contact and volume of liquid in circulation.

The concentration of total dissolved solids in a groundwater body may represent some of the significant characteristics of the environment through which the water moves. For instance high values of dissolved solids may indicate closed or partly closed basin or presence of relatively soluble minerals and their abundance or poor circulation of groundwater as aquifer of low permeability tend to increase the mineralization of groundwater. By far the most important technique in hydrologic studies is the use of isocones to trace the direction of the groundwater movement, as mineralization increases in the direction of groundwater flow.

Although there is no reliable method to make quantitative approximations from the qualitative data, it is however possible in some cases to delineate the areas of high permeability from areas of low permeability. Considering all other environmental factors, which control the mineralization of groundwater as constant in a flow system, it appears the concentration of dissolved solid is a function of hydraulic gradient. It can therefore be assumed that a close relationship exists between the isocones and piestolines. Closely spaced isocones may indicate either a change in formation or poor circulation which causes an increase in concentration in a comparatively shorter distance. However, a fairly good knowledge of groundwater flow, geology of the area and chemical processes occurring in the rock environment, is essential to draw such inferences with a reasonable confidence.

The interpretation of groundwater movement based entirely on mineralization of ground water may in certain circumstances be quite misleading. Mixing of water from different water bearing horizons, intrusion of brine or connate water from deeper zones and entrance of pollutants from surface may present entirely different picture. Chemical processes such as ion absorption, precipitation, sulphate reduction and softening of water by base exchange may also influence the shape of isocones significantly.

INDIVIDUAL ION CHANGES

The concentration of individual ions can be equally misleading in some cases, because reversal in case of sulphate is quite possible;

bicarbonate concentration has very limited range and cations are susceptible to base exchange. However, the isochloride (Eriksson and Khunakasem 1969) can be used in tracing the direction of ground water movement, except in cases where mixing between aquifer or chloride contamination from surface or deeper zones occurs. In bedrock aquifers, sometimes mixing is checked and runlets develop individual characteristics and as a result two wells 100 feet apart may give different values of individual ions concentration or total dissolved solids. Nevertheless, the isocones provide an extremely useful information if studied in proper perspective.

SAMPLING

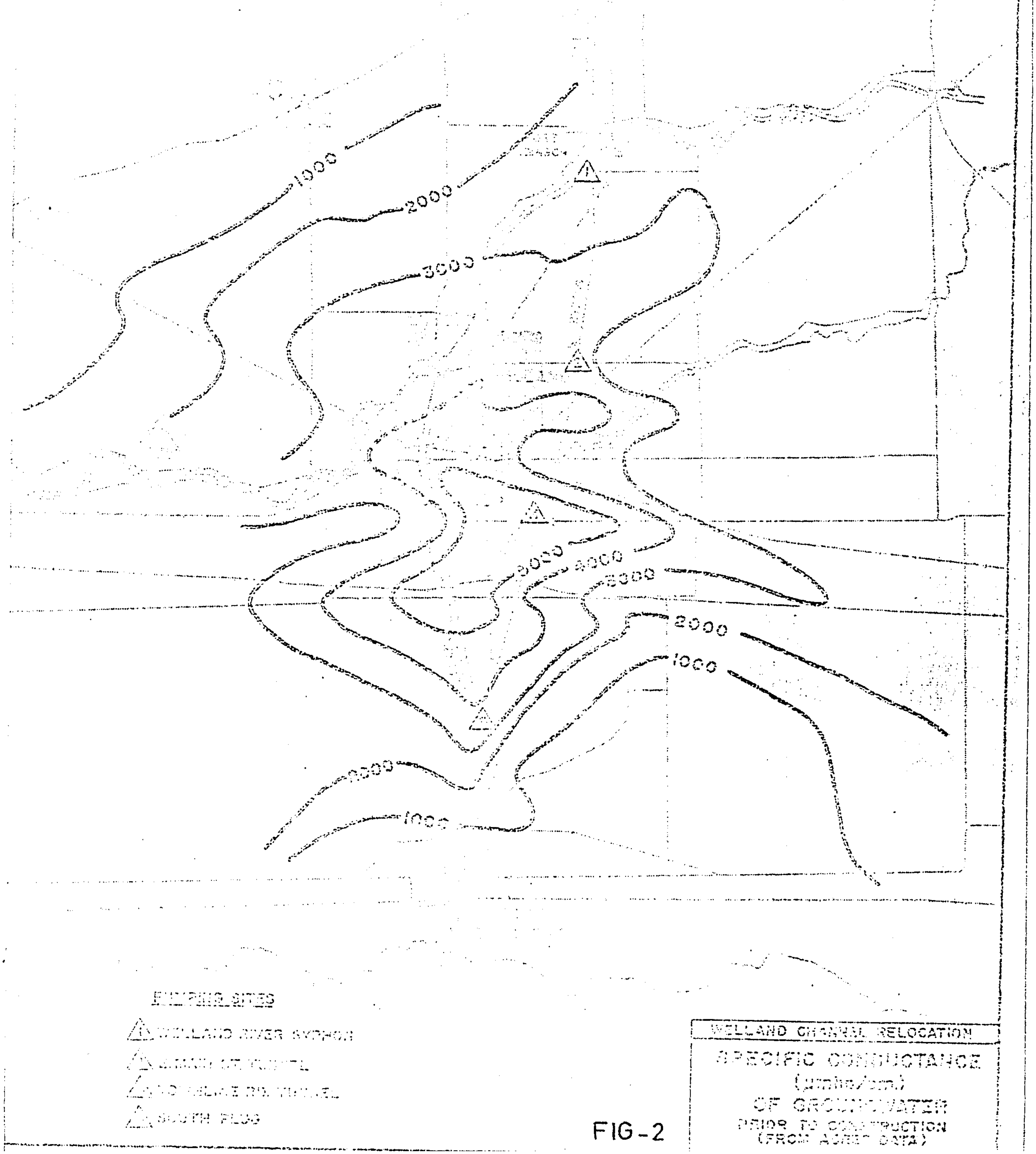
The validity of the samples determines the validity of the results, therefore the importance of sampling methods and analysis cannot be overlooked. The methods of sampling and analysis (Rainwater and Thatcher 1960) and presentation of the data are well described in literature and will not be discussed. However, for any interpretation based on mineralization of ground water, the depth of sampling plays a very important role.

If the samples are not collected from the proper depth, the variations in mineralization may represent variations in type and extent of flow system or variations in chemical composition of different formations. Thus, the knowledge of geology of the area and the depth to which the influence of a particular flow system extends is essential to establish a proper sampling depth.

To some extent the conditions under which a sample is collected such as from an operative well or from a well non-operative for a specific period of time or from piezometer which shows stratification of salinity, may also contribute towards erroneous results.

MINERALIZATION IN WELLAND AREA

The study conducted in the Welland area shows the relevance of some of the points made above. The preliminary assessment of ground water chemistry was made by obtaining numerous specific conductance measurements, shown in Figure (2), which provided an economic approach in selecting the locations of water samples for complete chemical analysis. The relationship between specific conductance and total dissolved solids is illustrated in Figure (3). A straightforward intepretation of isocones in Figure (4) indicates that ground water moves from Port Colborne and Fonthill areas toward south west of Welland city. The study of physical flow pattern and the chemistry of the soil and water in the confining overburden deposits did not substantiate the above conclusion. The installation of piezometric nests and analysis of water from different water bearing horizons indicate that high concentrations of total dissolved solids in the south west of Welland City was caused by upward leakage of NaCl type brine from deeper zones. The isocones demonstrate a general trend parallel to the piezometric contours, except where isocones start closing up due to the leakage of brine. The areas with lowest total dissolved solids occur to the northwest and southeast of the Welland city and coincide with piezometric and topographic highs. The mineralization


1000
2000
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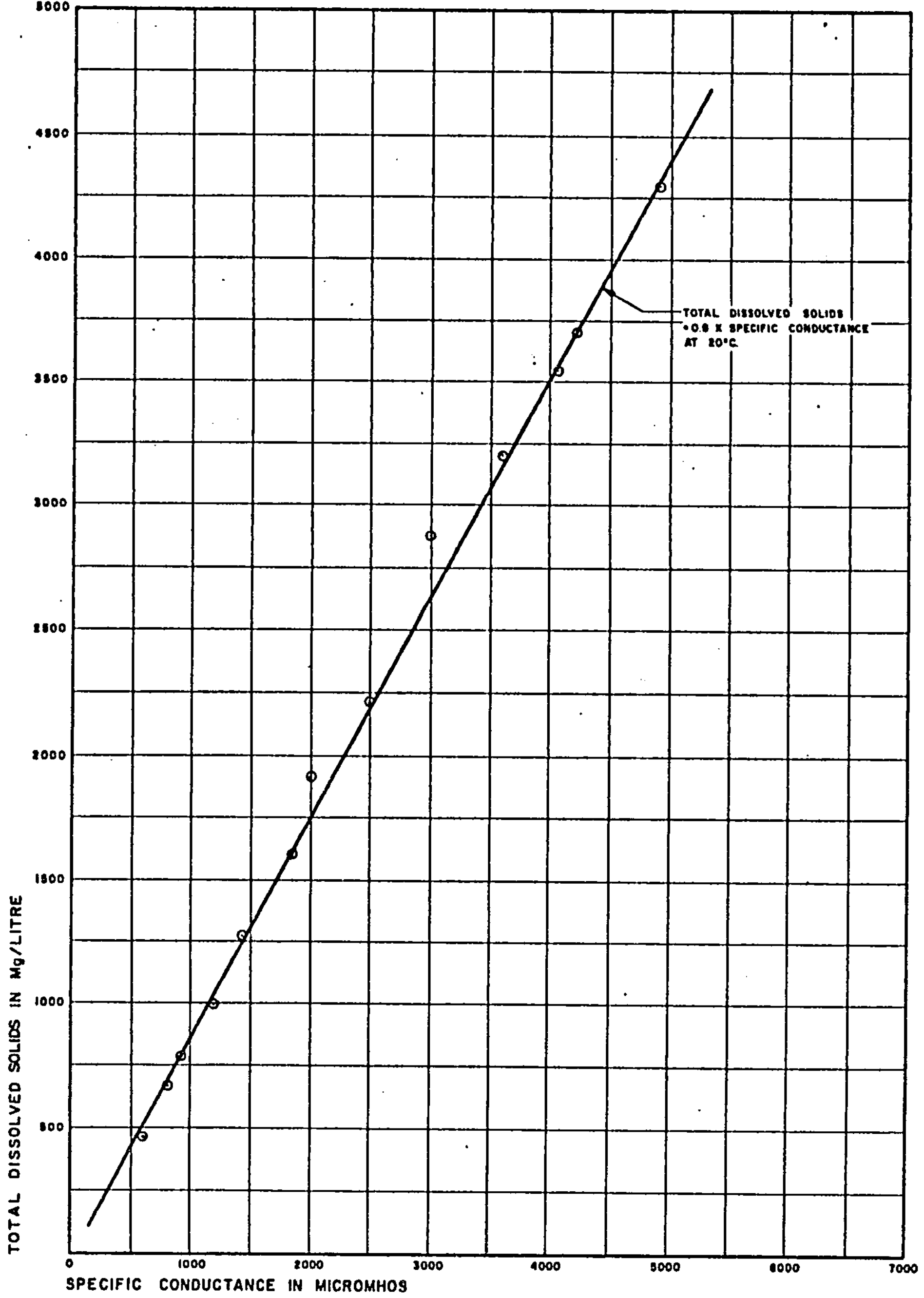
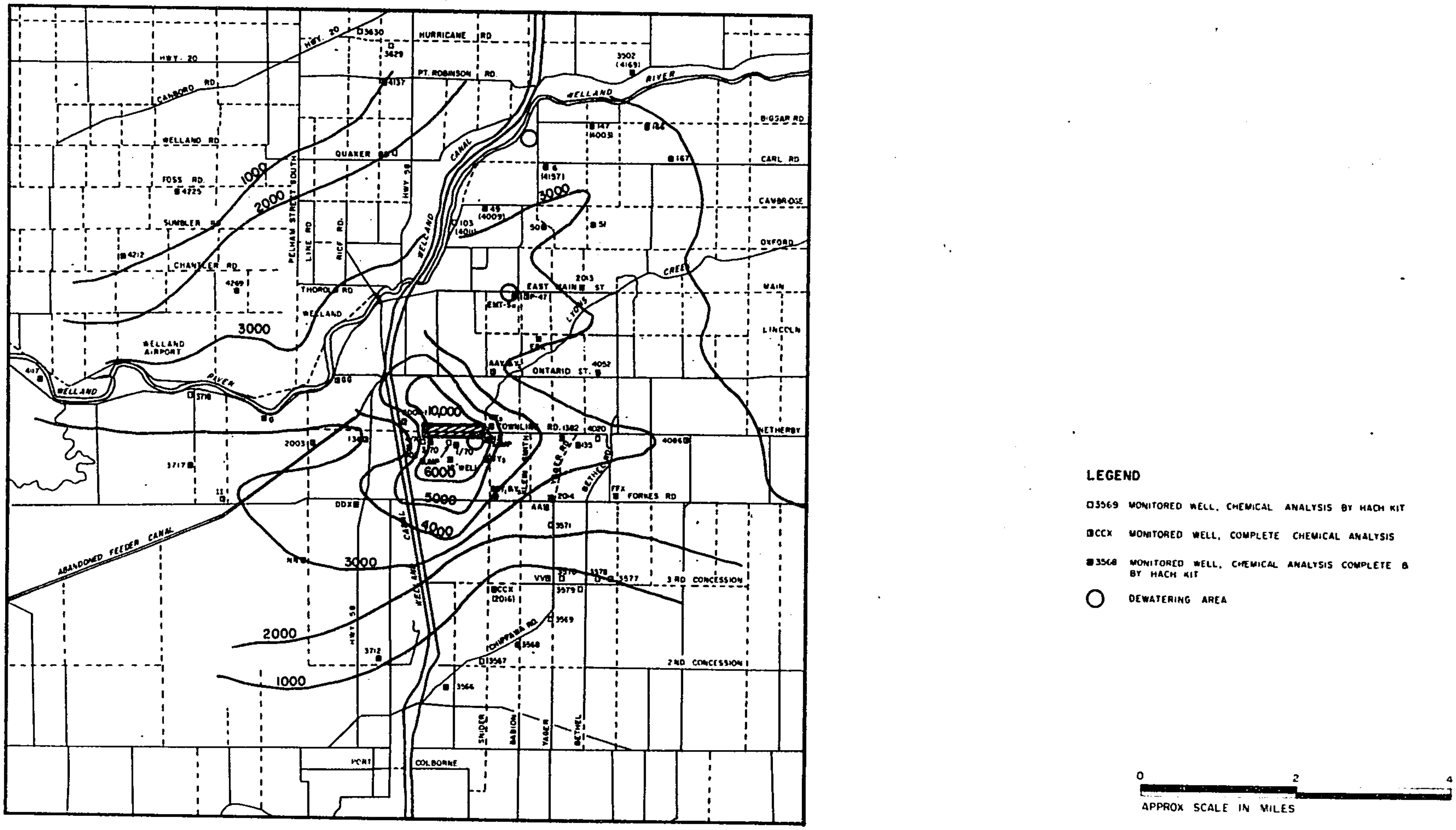
1000
PUMPING SITES
1 WELLAND RIVER SYPHON
2 MAIN ST. TUNNEL
3 TOWNLINE RD. TUNNEL
4 SOUTH PLUG
WELLAND CHANNEL RELOCATION
SPECIFIC CONDUCTANCE
(µmhos/cm.)
OF GROUNDWATER
PRIOR TO CONSTRUCTION
(FROM ACRES DATA)

FIG - 2



RELATION OF GROUNDWATER CONDUCTANCE TO TOTAL DISSOLVED SOLIDS

FIG-3



T.D.S. PRECONSTRUCTION

FIG - 4

of the whole region varies over a range of 350 mg/l to 14,000 mg/l.

The changes in mineralization with depth were also quite noticeable. In the central area the average values of total dissolved solids in overburden material ranged from 480 to 900 mg/l; in the upper 20 feet of bedrock from 1,000 to 10,000 and from 20 to 100 feet in bedrock from 10,000 to 150,000 mg/l.

In the central contaminated zone, the water samples from the wells which were inoperative for some time gave comparatively higher values of total dissolved solids. However, water samples collected after running the wells for some time showed a significant decrease in concentration. The salinity again built up as the pump was shut down and with renewed pumping the water cleared up of contamination. Similar conditions were observed in piezometers which had to be flushed before collecting the water samples.

The piezometers installed in deeper zones showed considerable stratification of salinity all along the water column. In situ conductivity measurements in some cases showed variations from 3,000 to 150,000 micromohs over a water column length of 80 feet.

Four dewatering wells installed around the tunnel excavation approximately 100 to 500 feet apart, gave different values of total dissolved solids, varying from 3,500 to 11,000 mg/l, indicating that where flow is controlled by fracture permeability, mixing of water from different horizons may impart different characteristics to individual runlets.

The well with 3,500 mg/l T.D.S. represented the character of water from main aquifer with minor amount of contamination. Other dewatering wells indicated different degrees of contamination.

CHANGES IN MINERALIZATION DUE TO DEWATERING

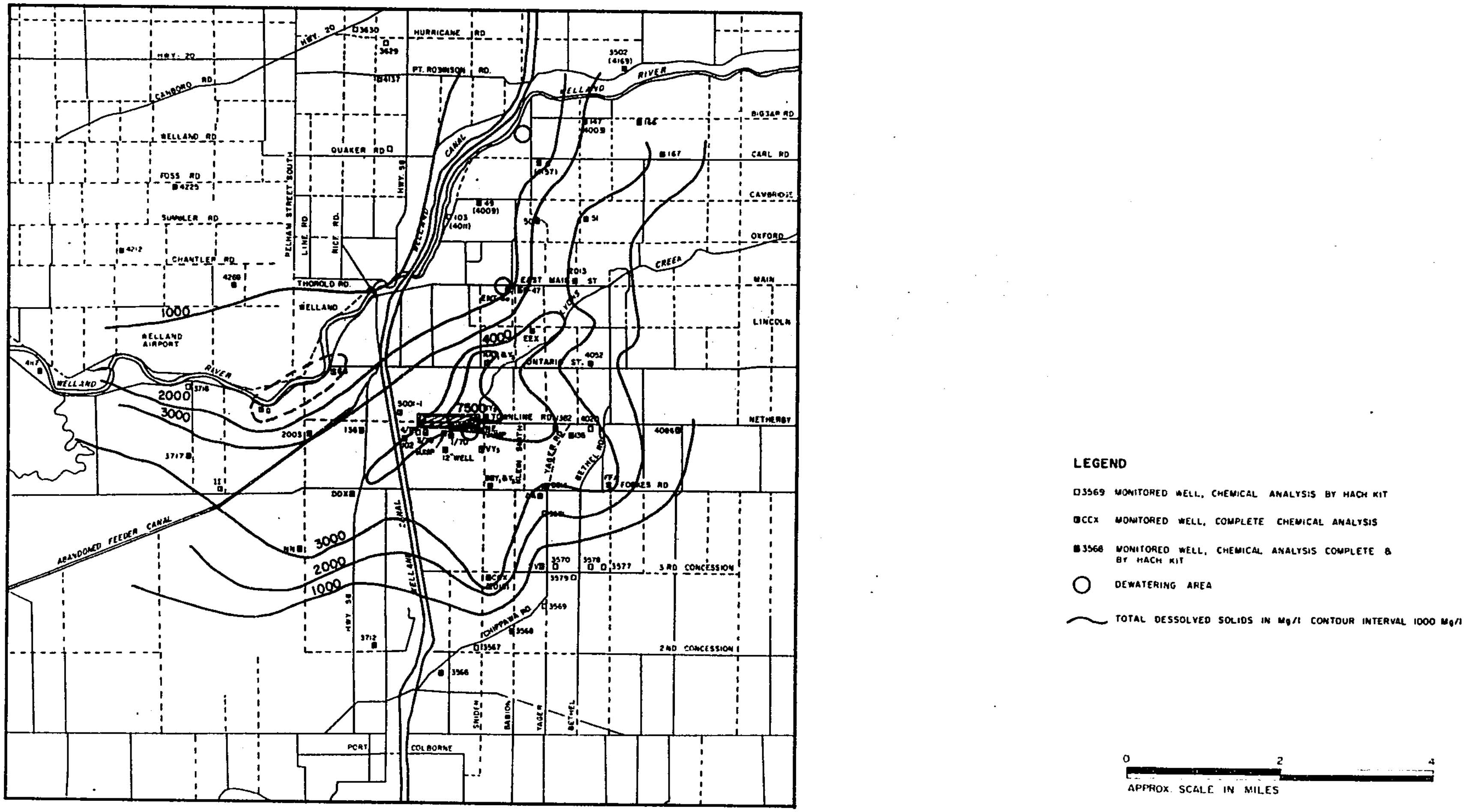
The pumping for dewatering purposes commenced on October 1968 at Townline Road Tunnel and Welland River syphon and produced significant physicochemical changes in the groundwater regime. The mineralization in the area around the tunnel site decreased to 3,970 mg/l (Figure 5). In the northeast direction where the leakage of brine is more predominant, the concentration of T.D.S. is in the range of 4,640 to 5,180 mg/l.

The groundwater with mineralization less than 1,500 mg/l invaded a vast area on the southeast of Townline Tunnel.

Although the inflow of brine due to larger head differential increased considerably after the pumping started, the build up of contamination was, however, checked by the high rate of discharge and flow velocity.

The demineralization which occured in the main aquifer due to change in hydraulic gradient was compensated partly by the intrusion of brine. At few locations no appreciable change in total dissolved solid was noticed, but the chemical composition of the groundwater was significantly changed. The decrease which occurred in the concentration of Ca and SO_4 ions was compensated by equal increase in Na and Cl.

The concentration of dissolved solids at Welland River syphon decreased from 3,600 mg/l to 1,000 mg/l after six months of pumping. It



CONCENTRATION OF TOTAL DISSOLVED SOLIDS DURING CONSTRUCTION

FIG-5

was observed that location of well, zone of influence of pumping, state of chemical equilibrium between soluble minerals and groundwater, and head differential between different water horizons are the principal factors in causing the chemical changes at that well location.

CHEMICAL INTERPRETATION OF GROUNDWATER MOVEMENT

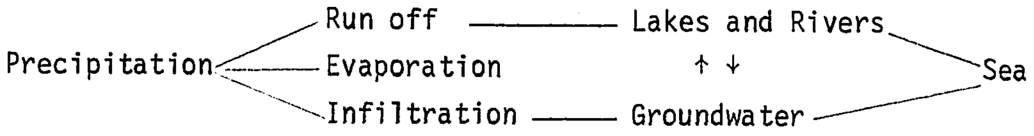
Weathering reactions take place primarily as a result of disequilibrium between the lithosphere and the hydrosphere, atmosphere and biosphere. The rate of decomposition of a mineral is a reflection of the differential between physical and chemical conditions at the time of formation and those existing at the present time.

Weathering takes place in rocks and soils and it is known to be more active at soil/rock contact. Below this it is active along the fracture openings and decreases with depth as opening become scarce or small.

Chebotarve (1955), after studying the changes in chemical composition of natural waters from different geological environments, stated "... the geochemical types of water changes with the increase of the total salinity as well as with increasing depth", and concluded that as the water travels from intake area the following sequential changes in chemical composition take place:

$$HCO_3 \rightarrow HCO_3 + Cl \rightarrow Cl + HCO_3 \rightarrow \begin{matrix} Cl \\ SO_4 \end{matrix} \text{ or } \begin{matrix} SO_4 \\ Cl \end{matrix} \rightarrow Cl \qquad \text{-------(1)}$$

The rainwater while falling through the atmosphere and percolating through the top soil picks up CO_2 to form carbonic acid gas which reacts with minerals to produce soluble bicarbonates. Looking at hydrologic cycle in a simplified form,



it becomes apparent that groundwater in recharge areas would have characteristics of activated rain water (i.e. predominantly HCO_3 type water) and on approaching the ultimate discharge area the composition of ground water would be similar to sea water (in terms of dominant ion). It is therefore obvious that groundwater would start as a HCO_3 type and on a large scale end up as Cl type water, regardless of the geology of the region.

$$HCO_3 \longrightarrow Cl \qquad \text{-----------------(2)}$$

However, there are two important questions to be considered, (i) What chemical changes take place between the two extremes and (ii) to what extent a sequence would advance in a particular flow system?

With regard to the first question it is evident that the chemical composition of groundwater during its travel from recharge area to discharge area is greatly influenced by the mineral composition of the earth materials and their relative solubilities. Hence the sequence between the two extremes (i.e. sequence (2)) would be primarily dependent on the geology of the region. The minerals of higher solubility and relatively greater abundance in natural environments are principal cause of changes in chemical composition of groundwater, therefore NaCl and $CaSO_4$

play major roles in the sequential changes. Groundwater moving through the geological environment where NaCl is predominant may undergo the following changes:

$$HCO_3 \rightarrow HCO_3 + Cl \rightarrow Cl + HCO_3 \rightarrow Cl \qquad \text{----------------(3)}$$

Since sulphate is generally present in natural environments, its concentration may gradually exceed HCO_3 concentration to introduce an additional step between Cl + HCO_3 and Cl type water.

$$\rightarrow Cl + HCO_3 \rightarrow Cl + SO_4 \rightarrow Cl \qquad \text{----------------(4)}$$

On the other hand in a $CaSO_4$ rich environment the following changes may occur:

$$HCO_3 \rightarrow HCO_3 + SO_4 \rightarrow SO_4 + HCO_3 \rightarrow SO_4 \rightarrow SO_4 + Cl \rightarrow Cl + SO_4 \rightarrow Cl \quad \text{----(5)}$$

Chebotarve's sequence also shows ulphate dominant water before the final change to chloride type water. It seems difficult to postulate such a change, because once Cl becomes dominant ion, it generally remains dominant, particularly near the final stages of the sequence. However, in a lower range of total salinity if Cl type water encounters SO_4 rich environment it is possible to have sulphate dominance over chloride. In higher range of total dissolved solids groundwater may reach equilibrium with sulphate, which is very rare in case of Cl because of its very high solubility, therefore in higher range of concentration Cl dominant water may not be replaced by SO_4 dominant water. Secondly, it is difficult to postulate such a change Cl + HCO_3 → SO_4 + Cl as shown in Chebotarve's sequence, because it is very rare for an ion to enter in this sequence, straightaway as dominant ion.

If at all this change occurs, it would take place in the following order:

$$Cl + HCO_3 \rightarrow Cl + SO \rightarrow SO + Cl \rightarrow Cl + SO_4 \rightarrow Cl$$

The limit to which the sequence would advance in a particular hydrogeological condition depends on the permeability and solubility of the material and the scale of the flow system. A complete sequence may exist in a very large flow system and a partial sequence in a smaller flow system. However, as Chebotarve stated, the sequential changes occur with the increase in salinity, it is possible therefore to expect a comparatively longer sequence in a smaller flow system if there is an abundance of soluble minerals (evaporites) or permeability values are very low. On the other hand, the sequence, in a larger flow system of higher permeability or with minor amount of soluble minerals may not advance to a significant length.

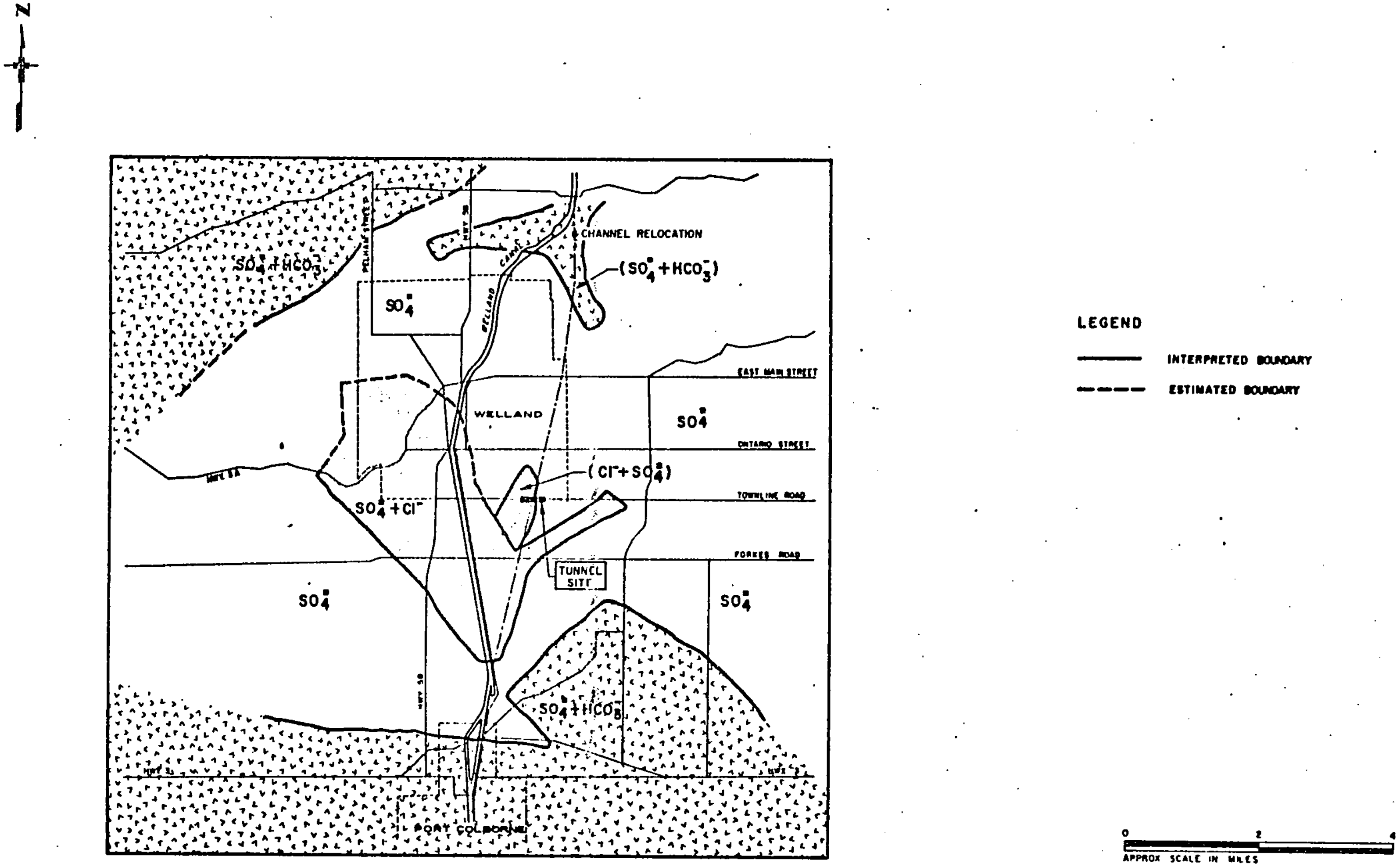
Mixing of water from different origins or reduction of sulphate by bacterial activity, may modify the sequence.

GEOCHEMICAL CHANGES IN WELLAND AREA

In the Welland area, the water type (dominant ion in solution) changed from HCO_3 and $HCO_3 + SO_4$ at the recharge areas to a water of relatively high sulphate concentration as it travelled down gradient. In the vicinity of the Welland Townline Road Tunnel the groundwater finally changed to predominantly Cl type. The changes from recharge areas to tunnel site occurred in the following sequence:

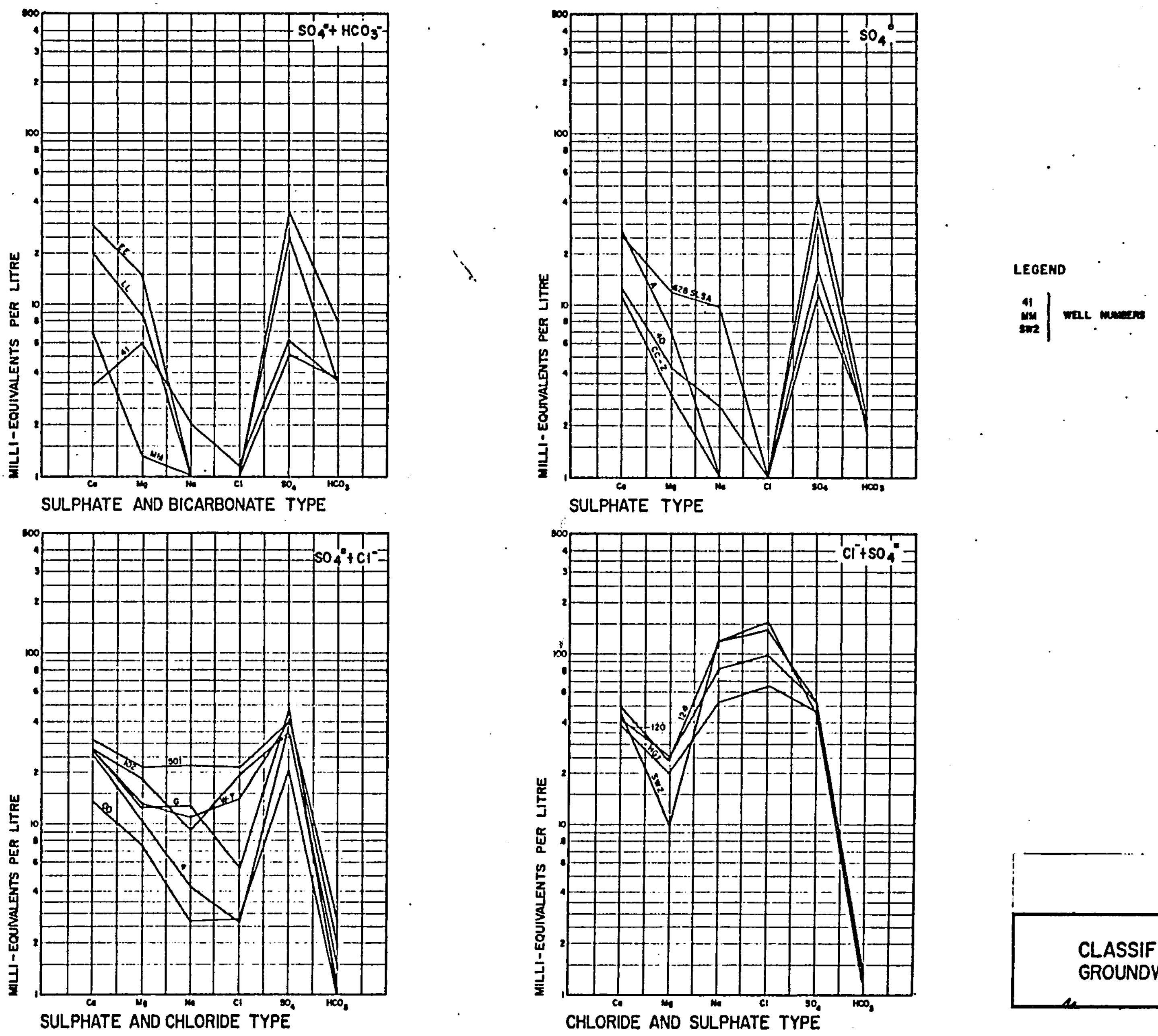
$HCO_3 \rightarrow HCO_3 + SO_4 \rightarrow SO_4 + HCO_3 \rightarrow SO_4 \rightarrow SO_4 + Cl \rightarrow Cl + SO_4 \rightarrow Cl$

Predominantly HCO_3 type water and lowest total dissolved solids in the areas of topographic and piezometric highs confirmed the locations of recharge areas (Figure 6). Abundance of gypsum in the salina formation was reflected by SO_4 dominant water in the central region. However, the indication of the tunnel site being a discharged area by Cl type water was contrary to all other observations. The increase in Cl appeared to be too sudden to be interpreted as sequential change, which is a function of time and length of travel path of groundwater. It was found that NaCl type brine in the deeper zones had the same chemical composition as that of NaCl type water in the main aquifer at Townline Tunnel site (Figure 7). However, the water in the main aquifer showed lower concentration due to dilution with fresh water. The upward leakage of brine was probably occurring through abundant improperly plugged gas wells around the tunnel area. These water types when plotted in a semilogarithmic graph showed distinct pattern (Figure 7). The SO_4 type represents water from the main aquifer, $Cl + SO_4$ type represents water from deeper zones (i.e. brine) and $SO_4 + Cl$ type the mixture of fresh water and brine. By plotting maximum and minimum concentration of an ion in a particular type of water (Figure 8), the relative continuity of gradual increase in concentration of an individual ion became quite apparent in case of Ca, Mg, HCO_3 and SO_4, while there was a distinct discontinuity in case of Na and Cl. It also indicated that origin of Na and Cl is not in the main aquifer and the $SO_4 + Cl$ type water is a result of mixing of two different types of waters.



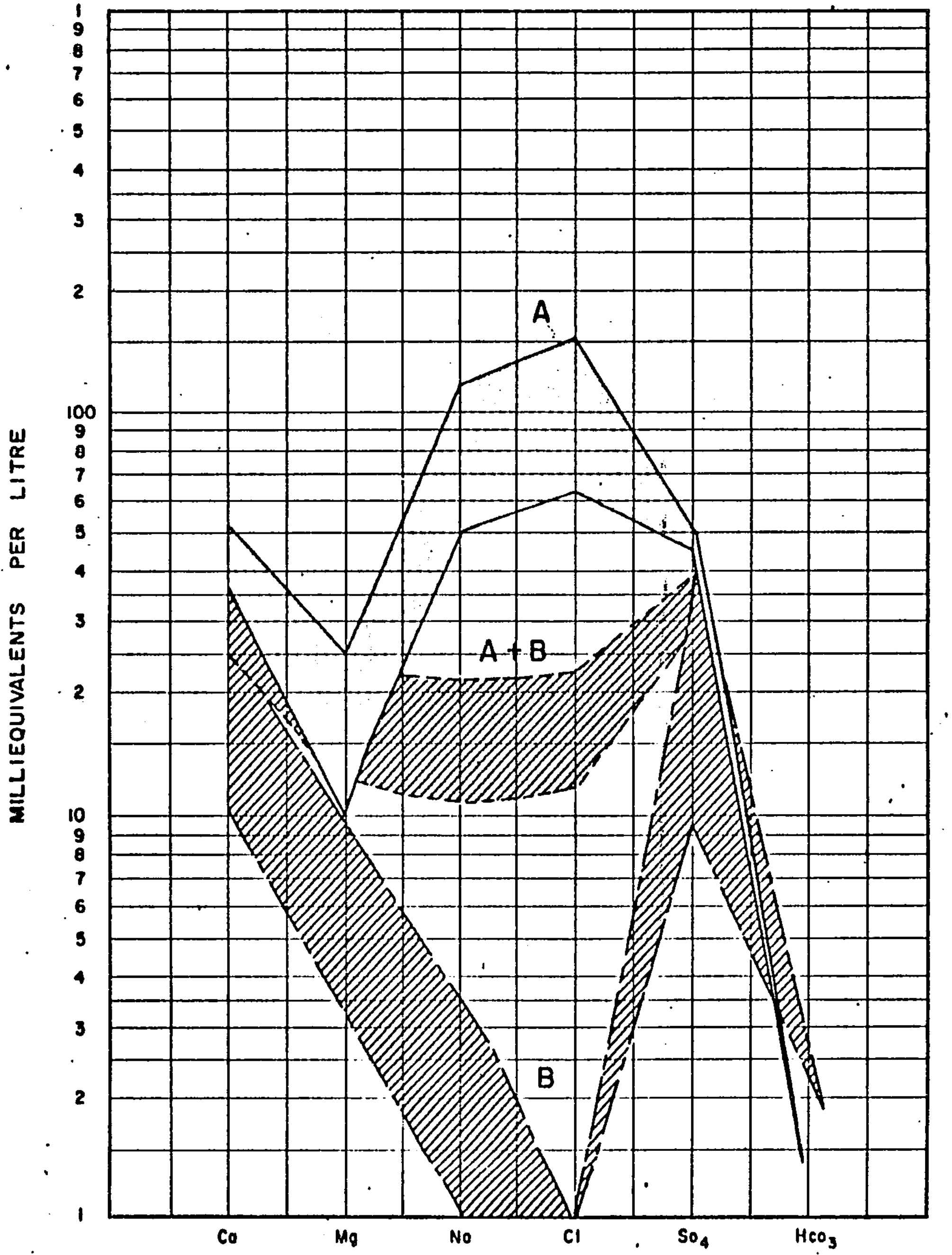
ZONATION OF
GROUNDWATER TYPES
PRIOR TO CONSTRUCTION

FIG - 6



CLASSIFICATION OF GROUNDWATER

FIG-7



LEGEND

A = NACL TYPE BRINE FROM DEEPER ZONES

B = SO_4 DOMINANT WATER FROM MAIN AQUIFER

A+B = MIXTURE OF BOTH TYPES

DIFFERENT GROUPS OF WATER

FIG - 8

SK-1684-A-

CHANGES DUE TO DEWATERING

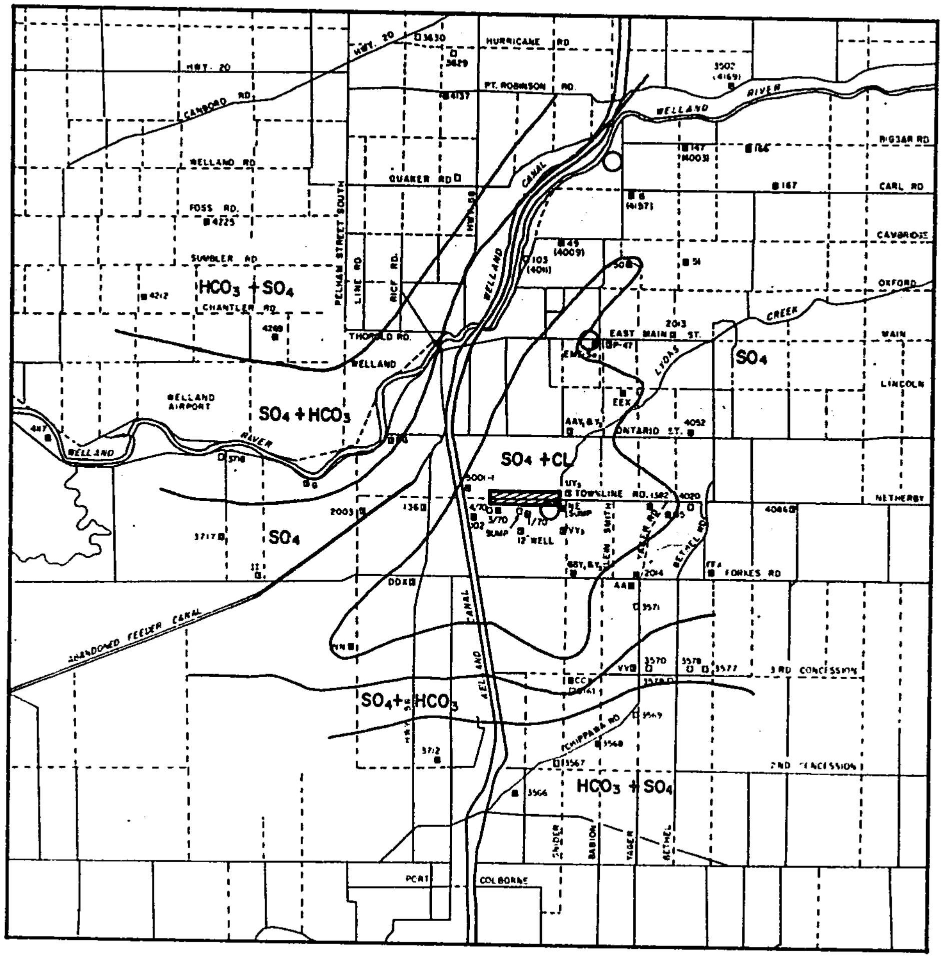
The contamination accumulated around tunnel site was flushed out after a short period of pumping. However, the heavy pumping resulted in a greater head differential between the water in the deeper zones and the main aquifer, within the zone of influence of pumping. Although the overall upward leakage of brine was increased considerably and spread over a wider area, the increase in flow velocity did not allow the NaCl brine to accumulate in a higher concentration. Therefore, Cl type water disappeared and SO_4 + Cl (mixed water) spread over a wider area. The sequence found under the natural flow conditions was reduced due to changes in flow conditions to:

$$HCO_3 \rightarrow HCO_3 + SO_4 \rightarrow SO_4 + HCO_3 \rightarrow SO_4 \rightarrow SO_4 + Cl$$

The area occupied by $HCO_3 + SO_4$ and $SO_4 + HCO_3$ type waters extended under the altered flow conditions on the expanse of area occupied by SO_4 type water (Figure 9). In fact, SO_4 + Cl type water would probably have been only SO_4 type water if there had not been an upward intrusion of NaCl brine. In other words, without the upward intrusion of Cl type water, the sequence would have been:

$$HCO_3 \rightarrow HCO_3 + SO_4 \rightarrow SO_4 + HCO_3 \rightarrow SO_4$$

It is interesting to note, where there have been only a partial sequence present, changed circumstances resulted in a complete sequence.



LEGEND

□3569 MONITORED WELL, CHEMICAL ANALYSIS BY HACH KIT

▣CCX MONITORED WELL, COMPLETE CHEMICAL ANALYSIS

■3568 MONITORED WELL, CHEMICAL ANALYSIS COMPLETE & BY HACH KIT

○ DEWATERING AREA

0 2 4
APPROX. SCALE IN MILES

CHEMICAL ZONATION
OF GROUNDWATER
DURING CONSTRUCTION

FIG - 9

PHYSICOCHEMICAL EQUILIBRIUM

The groundwater is continually dissolving and precipitating material and is always attempting to attain chemical equilibrium with its surrounding. The rate with which water approaches equilibrium with its environments is governed by many variables. The range of solubility of minerals found in the earth's crust is so wide that existence of a complete state of equilibrium with the environment is inconceivable as far as weathering processes are concerned. However, studies can be made to determine the state of chemical equilibrium between the groundwater and the minerals which contribute towards mineralization of ground water.

Measurement of departure from chemical equilibrium aid in delineating principal areas of recharge and in predicting areas subjected to solution or deposition of minerals. The equilibrium studies also help in understanding the chemical behaviour of the mineral which control the chemistry of water and changes that may occur with the elapse of time or because of changes in hydraulic gradient. In many complicated cases, interpretations on the basis of concentration, ionic relation and metamorphosis of groundwater become more meaningful and less ambiguous if carried out in conjunction with the equilibrium studies.

The chemical equilibrium in a groundwater regime is partly dependent on the physical equilibrium between recharge and discharge, therefore it seems more appropriate to use the term "physicochemical equilibrium".

One of the important aspects in equilibrium study is the establishment of a proper value of the equilibrium constant K_{eq}, because the solubility characteristics of minerals may vary in different hydrogeological environments. In general the solubility of a solid depends upon the difference between the energy consumed in separating the ions or molecules from the crystal lattice and the energy released by the solution of these ions or molecules (hydration energy). For instance the solubility of gypsum is partly described by

$$K_{eq} = \alpha_{Ca} \quad \alpha_{SO_4}$$

where K_{eq} is the equilibrium constant and α is the activity of the ion species Ca^{++} and SO_4^{--}. Values of 2.4×10^{-5} and 2.45×10^{-5} have been reported by Latimer (1952) and Moreno and Osborn (1963) respectively for K_{eq} at 25 degrees C. The solubility of $CaSO_4$ can be significantly influenced by the chemical character of water, mode of occurrence of mineral (gypsum or anhydrite), variations in temperature, nature of crystal material, the energy of crystal lattice, grain size and the impurities involved. With increasing NaCl concentration the solubility of gypsum is enhanced because of the decrease in the activity of Ca^{++} and SO_4 (ionic strength effect). On the other hand with increasing $CaCl_2$ or $MgSO_4$ concentration the solubility of gypsum is reduced (common ion effect). Since natural waters are highly complex solutions, it is evident that values of constants determined in the laboratories or by theoretical computation would not be a proper criteria for such a complex situation, unless these values are modified to account for the environmental control on the solubility of the mineral.

INFLUENCE OF PUMPING ON CHEMICAL CHARACTER

Hendriekson and Krieger (1964) pointed out: "In recent investigations reports of mineralized water being replaced by fresh water after pumping are rare. On the contrary most reports indicate that where changes in chemical character occur the water increases in mineralization with continued pumping". The generalization of such reports appear to be oversimplification of a complex situation. The nature of the aquifer (confined or unconfined) physical flow pattern, design of the well, location of the well and the rate of pumping are principal factors in bringing about the changes in mineralization of water at the pumping site. In a particular flow system, assessing the major flow being downward and horizontal, the increase in hydraulic gradient would as a principle result in a decrease of mineralization of groundwater. If the length of the flow path is constant an increase in velocity would result in decrease of time of contact between mineral and water, therefore demineralization will occur. However, there is always a possibility of movement of water from deeper zones especially in the case of partially penetrating wells. Increase in mineralization in case of upconing would depend on the rate of pumping. In an unconfined aquifer higher rate of pumping from a local flow system may induce flow from intermediate and regional flow systems which contain water of relatively higher concentration. Location of the well close to the recharge area is more likely to reduce the mineralization of groundwater. If the well is located in an area where the groundwater is in equilibrium with the dominant mineral in solution and the zone of influence of pumping does not intercept the boundary of physicochemical equilibrium, no significant change may take place.

EQUILIBRIUM STUDY IN WELLAND AREA

The modification of theoretical K_{eq} was obtained by comparing the theoretical results with the graphic analysis of data actually obtained from the study area. The solubility product of Ca HCO_3 is controlled by the concentration of $CaSO_4$ in solution and the solubility of $CaSO_4$ is influenced by the increasing concentration of NaCl. Scholler (1962) calculated the effect of variations in temperature and NaCl concentration on the solubility of $CaSO_4$:

Temperature	(Ca) (SO_4) mole/litre
0°C	1.67×10^{-4}
10°C	1.99×10^{-4}
18°C	2.19×10^{-4}
30°C	2.37×10^{-4}

and

NaCl	(Ca) (SO_4) mole/litre at 14°C
0 g	1.56×10^{-4}
0.2925	2.90×10^{-4}
8.850	4.20×10^{-4}

Since the temperature of groundwater in Welland area was generally steady between 10 degrees and 11 degrees, it was considered constant for practical purposes. Other two factors (ionic strength "U" and NaCl concentration) which affect the solubility of gypsum were plotted separately against (Ca) (SO_4) product (Figure 10 and Figure 11).

The curve U vs (Ca) (SO_4) indicated that at U = 0.058 and

$(Ca)\ (SO_4) = 2.0 \times 10^{-4}$ the further increase in $CaSO_4$ concentration is very little, therefore it can be approximated that saturation of $CaSO_4$ is reached at this point in water not much influenced by NaCl. These values conform very closely with the values calculated by Scholler. The (Na)(Cl) vs $(Ca)(SO_4)$ graph also indicated that saturation is reached at $(Ca)(SO_4) = 2.0 \times 10^{-4}$ and the concentration of $CaSO_4$ is not influenced by NaCl as long as its concentration is less than $(Na)(Cl) = 5.0 \times 10^{-5}$ mole/litre. Similar graphic interpolations were used after applying the non ideality corrections and a value of $K_{eq} = 3.2 \times 10^{-5}$ was approximated for the Welland area.

INFLUENCE OF PUMPING

The results of equilibrium study were projected on a plan of study area to separate the areas where the groundwater is in a state of equilibrium with soluble gypsum, from the areas where solution and leaching of gypsum is still active (Figure 12). The boundary between saturated and unsaturated water with respect to gypsum moved in significantly as a result of heavy pumping at Townline Road Tunnel and Welland River syphon sites.

The changes on the north side are more pronounced as the cone of depression produced by the well at syphon site extended far beyond the boundary of saturated water. The quality of the water at syphon site improved considerably as total dissolved solids decreased from 2,800 mg/l to 1200 mg/l. In contrast the groundwater at Townline Road Site (disregarding the effect of NaCl brine) showed minor variations

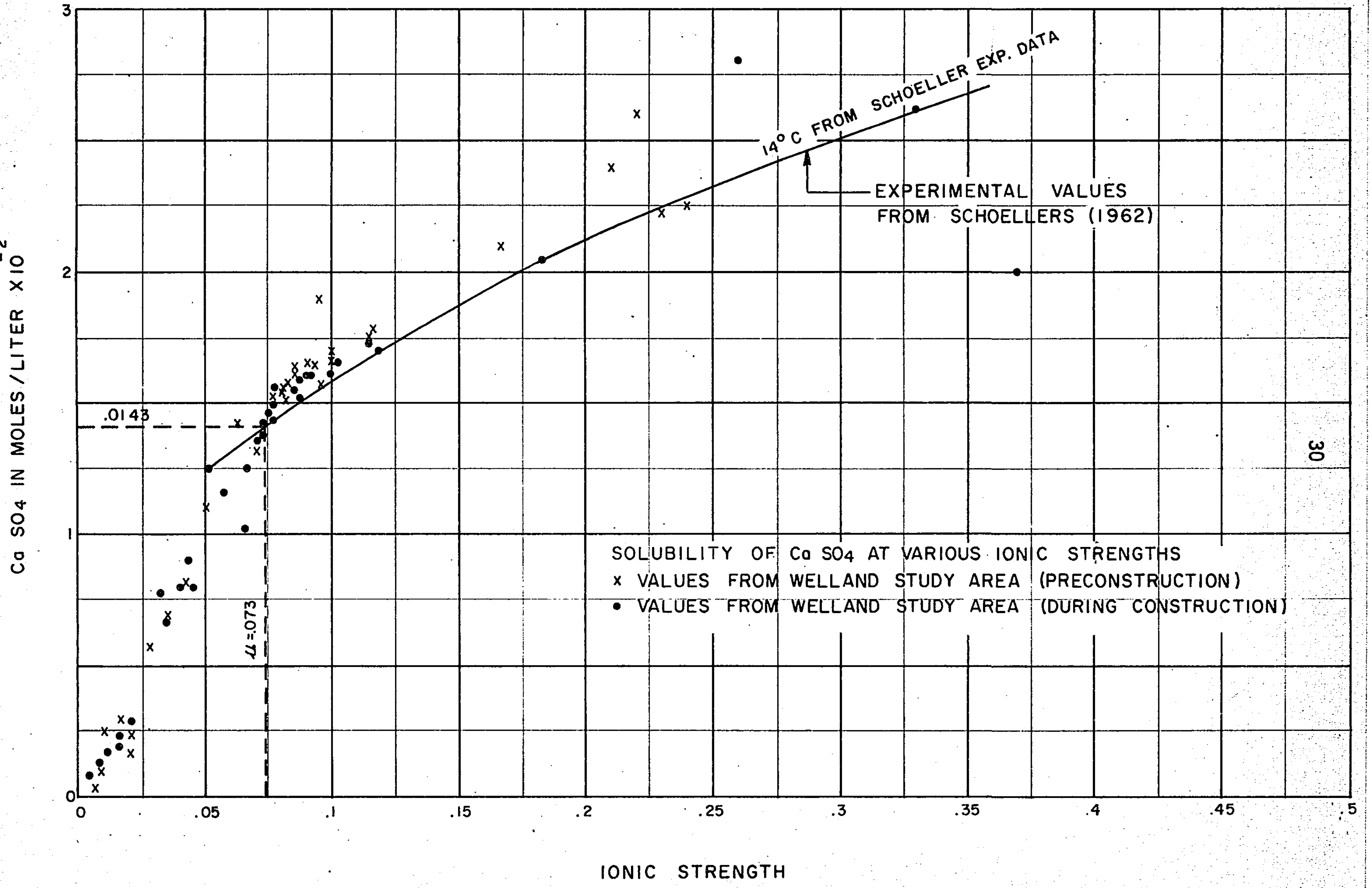

14° C FROM SCHOELLER EXP. DATA
EXPERIMENTAL VALUES
FROM SCHOELLERS (1962)
SOLUBILITY OF Ca SO4 AT VARIOUS IONIC STRENGTHS
x VALUES FROM WELLAND STUDY AREA (PRECONSTRUCTION)
• VALUES FROM WELLAND STUDY AREA (DURING CONSTRUCTION)
.0143
μ=.073
Ca SO4 IN MOLES/LITER X10⁻²
0
1
2
3
0
.05
.1
.15
.2
.25
.3
.35
.4
.45
.5
IONIC STRENGTH

FIG-10

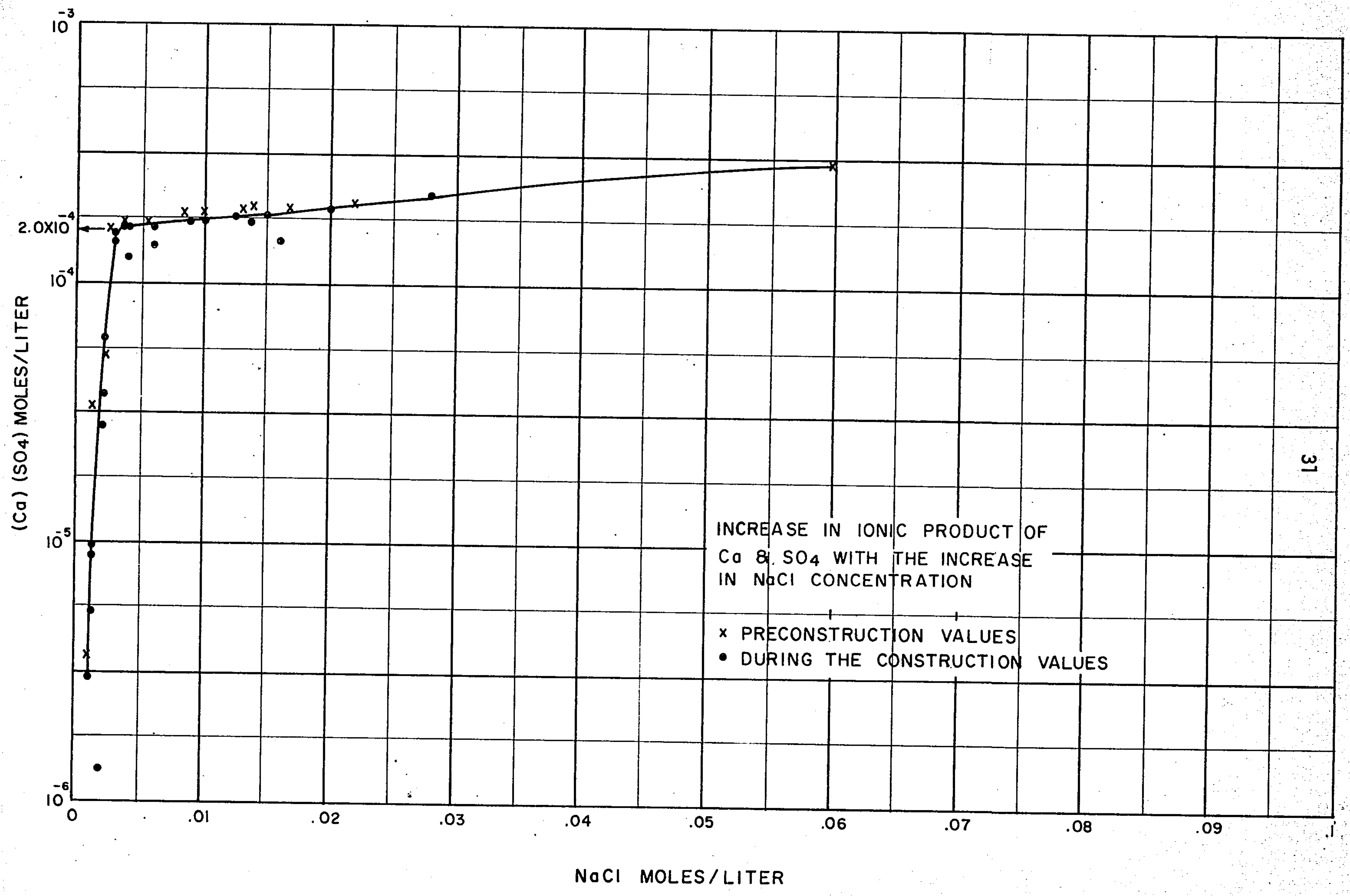
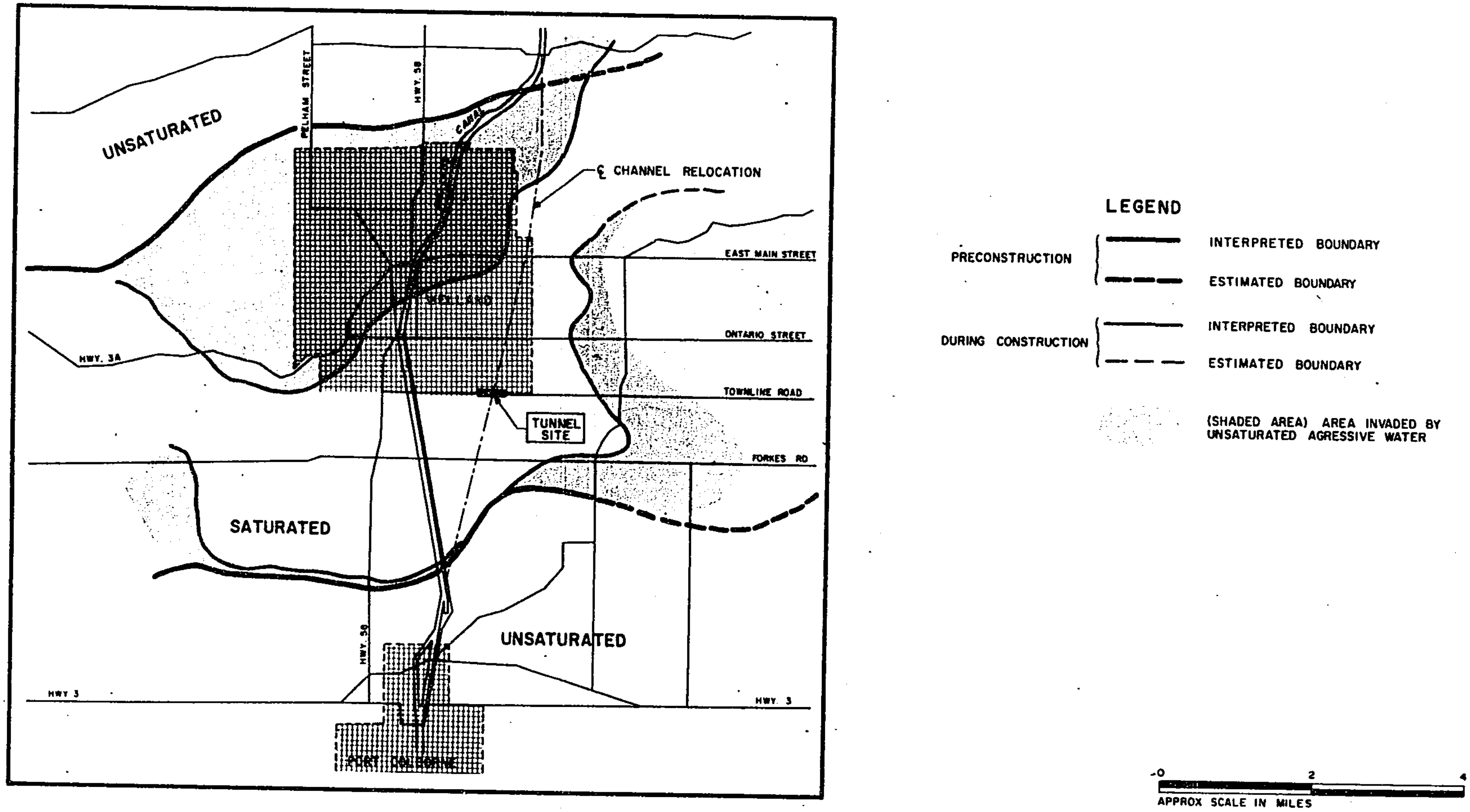

INCREASE IN IONIC PRODUCT OF
Ca & SO₄ WITH THE INCREASE
IN NaCl CONCENTRATION
x PRECONSTRUCTION VALUES
● DURING THE CONSTRUCTION VALUES
10^{-3}
2.0×10^{-4}
10^{-4}
10^{-5}
10^{-6}
(Ca) (SO4) MOLES/LITER
0
.01
.02
.03
.04
.05
.06
.07
.08
.09
.1
NaCl MOLES/LITER

FIG-11



MOVEMENT OF SATURATION BOUNDARY

FIG-12

in dissolved solids. It is therefore possible in certain hydrogeological environments to determine the optimum location of a well system which may produce the minimum changes in groundwater chemistry or which may help in bringing about the rapid improvement in water quality.

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APPENDIX II

APPENDIX II

A Summary of Development of Concept of Basin-Wide Groundwater Circulation

1. INTRODUCTION

Less than 10 years ago, very little was known about the relation of geology to basin-wide circulation of groundwater. The hydrologists and applied mathematicians remained preoccupied through the period 1935-1960 with the problems associated with well hydraulics, probably due to the immediate applicability of these studies in determining the local aquifer conditions. Since the publication of Hubber's classic paper "The Theory of Ground Water Motion" in 1940, scarcely any attention was paid till the early sixties to the large scale regional effects of groundwater motion.

In the 1960's attention was turned to regional situations with groundwater basins as units of study, primarily due to the stimulating work of Ernst (1962), Toth (1962) and Meyboon (1962).

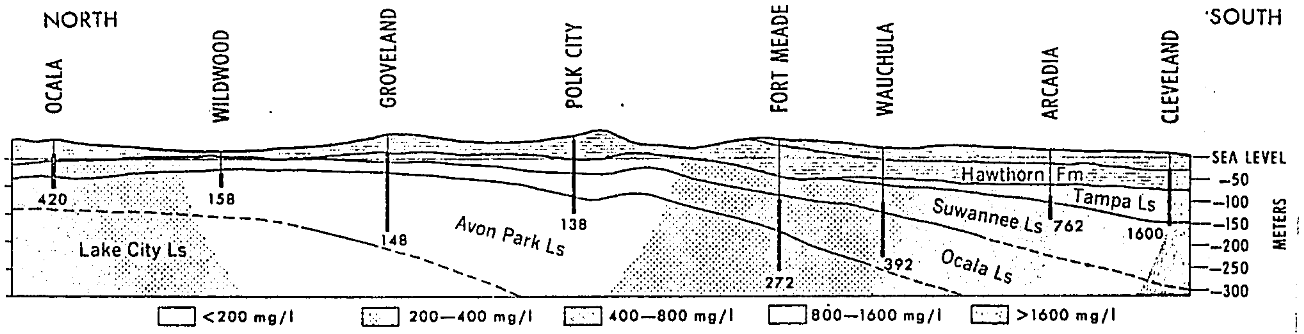
The study of groundwater is a study of a dynamic system from its source in the area of recharge through its flow system to its end in the area of discharge. The eventual aim of all studies is to gain a full knowledge of the quantity and quality of water entering the flow system, where it flows, what chemical changes take place and where it discharges. Therefore, among numerous features, the studies of groundwater motion on a regional scale are primarily directed to establish the following important features: location and extent of recharge and discharge areas, direction and velocity of flow at any point and depth and nature of flow system.

As in the transient field individual well is used as a unit of study, in the regional situation, drainage basins have been chosen as the most practical unit of study. The drainage basin is an area encompassing the surface flow-system and investigations show that to a certain extent it coincides closely with associated groundwater flow system.

The analysis of regional groundwater flow can be carried out using field techniques, such as geochemical correlation, piezometric interpretation and geobotanical mapping or using model techniques.

A geochemical model, based on principles of chemical thermodynamics was first developed by Back (1963). A chemical equilibrium model and a study of radiocarbon isotopes was used by Hansaw, Back and Rubin (1967) as shown in Figures 1 and 2, in order to identify principal recharge areas and to calculate apparent velocity in central Florida regions.

Meyboon (1962) on the basis of field observations, measured the groundwater flow in a stratified medium and called the model Prairie Profile. In addition to piezometric data, geobotanical data was also utilized to identify groundwater outcrops.



Concentration of dissolved solids in milligrams per liter (mg/l).[3]

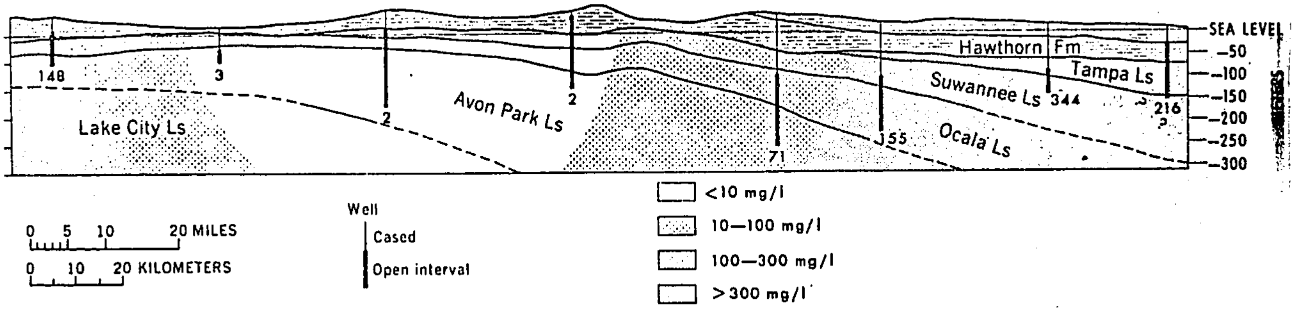


Figure 1

Concentration of sulfate ion in milligrams per liter.

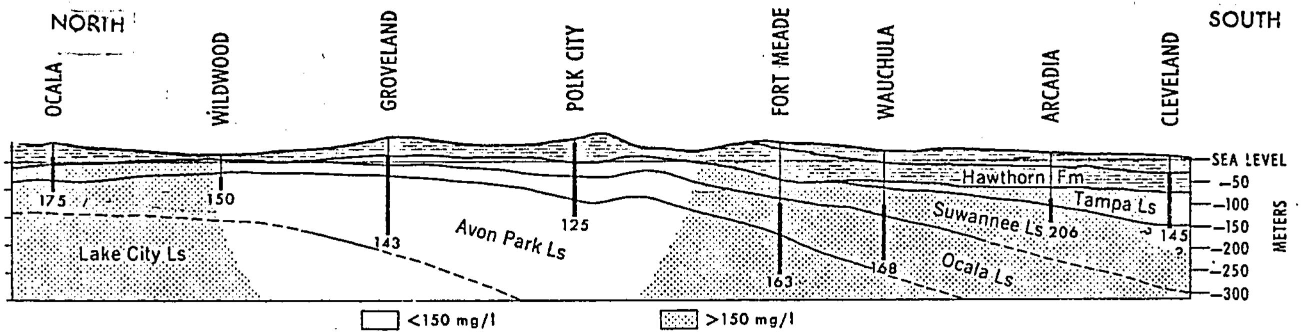


Fig. 4a — Concentration of bicarbonate ion in mg/l.

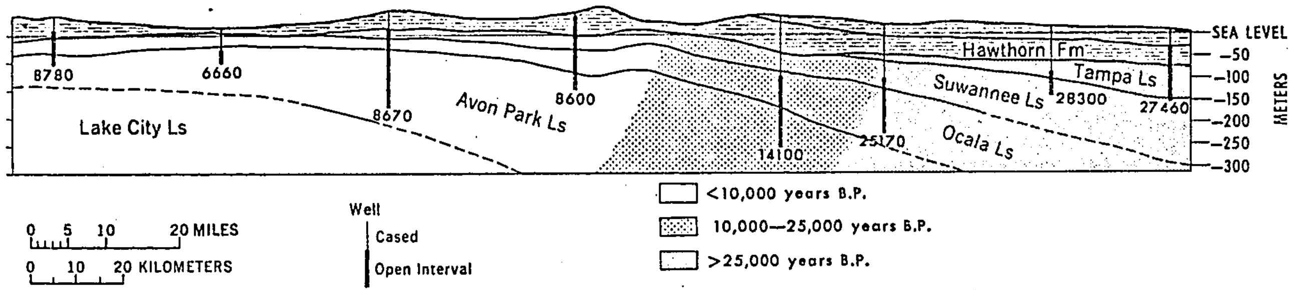


Figure 2

Radiocarbon ages in apparent years before present (B.P.).

In modelling technique, most versatile are so-called mathematical models. Both analytical and numerical methods have been used by Toth (1962) and Freeze and Witherspoon (1966) to verify the original concept of Hubbert as well as to describe details of water motion as influenced by variations of permeability and water table configurations.

The development and understanding of ground water flow systems have added significantly to the usefulness of regional groundwater studies because the proper understanding of the flow system is prerequisite both to meaningful measurements of the groundwater balance and to simulating the groundwater flow in a model.

This paper is directed particularly at the hydrology of the basin-wide circulation of groundwater, with emphasis on the development of concept followed by a consideration of potential research needed in some of the aspects of general topic. Only the broader principles and factors influencing the flow system are considered.

2. DEVELOPMENT OF CONCEPT

The seeds of the present thought can be traced as far back as 1906. Fourmarier (1939) cited a model as shown in Figure 3, developed by D'Andrimont in 1906 with laboratory experiments, demonstrating the circulation of ground water in a homogeneous isotropic medium.

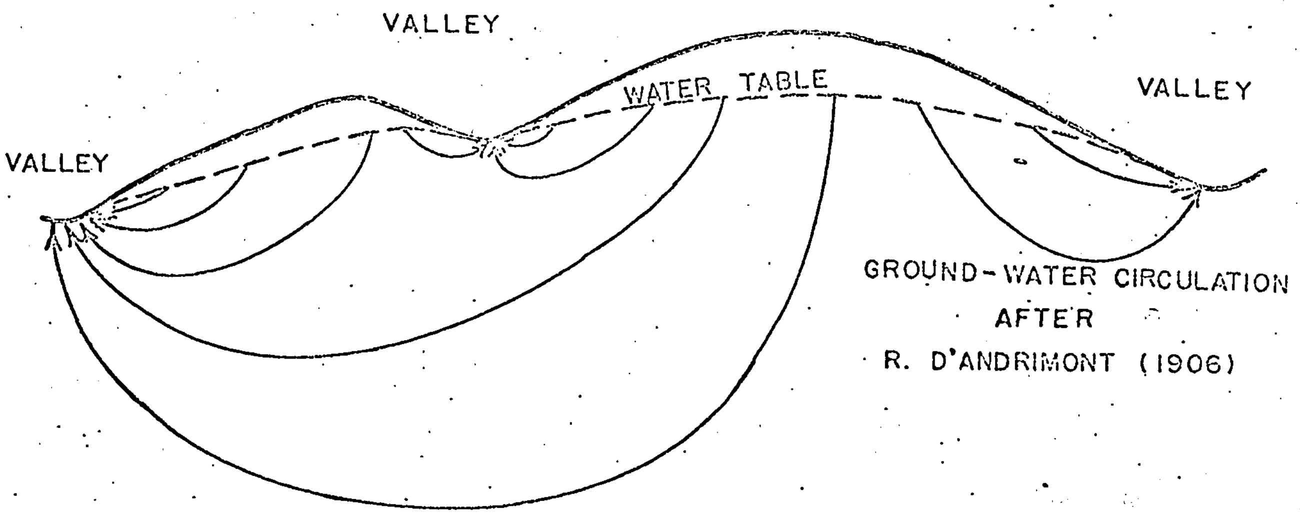


Figure 3--Circulation of ground water in homogeneous materials according to laboratory experiments of R. D'Andrimont

More than 64 years ago D'Andrimont demonstrated the existence of secondary sub-basin circulation.

Important features such as pronounced influence of topography and possible development of local flow system superimposed on regional flow systems are quite conspicuous in this model. Recharge areas are extended all through the slope of the surface and discharge is concentrated only at the bottom of the valleys.

3. HOMOGENEOUS MEDIUM

However, it was King Hubbert (1940) who for the first time described the mechanics of gravitational flow in a homogeneous isotropic medium. He presented the physical laws governing the steady state flow in their exact mathematical framework.

The most important property of groundwater with respect to movement is its potential, defined by Hubbert: "The amount of work required to transport a unit of mass of the fluid from an arbitrary chosen standard state to the state at the point under consideration". The general mathematical expression for fluid potential at a point P can be written as:

$$\emptyset = gz + \int_{Po}^{p} \frac{dp}{P} + \frac{v^2}{z} \qquad \text{(Hubbert Eq. 28)} \quad \text{-----------------(i)}$$

where

$\emptyset$ = total fluid potential

g = acceleration due to gravity

z = elevation

P = pressure

v = velocity

p = fluid density

The flow velocity of groundwater is extremely slow, therefore the above expression can be simplified to:

$$\emptyset = gz + \int_{Po}^{p} \frac{dp}{P} \qquad \text{(Hubbert Eq. 30)} \quad \text{-----------------(ii)}$$

For liquid potential further reduces to:

$$\emptyset = gz + \frac{P - Po}{P} \qquad \text{(Hubbert Eq. 31)} \qquad \text{----------------(iii)}$$

The choice of standard datum is arbitrary. Hubbert considered it convenient to choose sea level and atmospheric pressure as reference states.

z_o = zero P_o = 1 atmosphere

In most of the mathematical models, the assumed impermeable basal boundary is considered as standard datum (z = 0).

However when pressure is atmospheric on any point on the water table the expression (iii) reduced to:

$$\emptyset = gz$$

All mathematical models of basin-wide groundwater flow are based on this fundamental concept, and they are developed by predicting the distribution of the fluid potential by using analytical or numerical method, within the framework of boundaries defined by groundwater divides (vertical), impermeable basement (horizontal), and water table configuration (upper boundary) etc.

Hubbert described the flow pattern in a homogeneous, isotropic medium shown in Figure 4 as consisting of sources (high potential) distributed over the air-water interface and the sinks (low potential) limited to the bottom of the valleys containing streams. The flow is solenoidal and no flow lines can intersect each other. The potentials at the sources

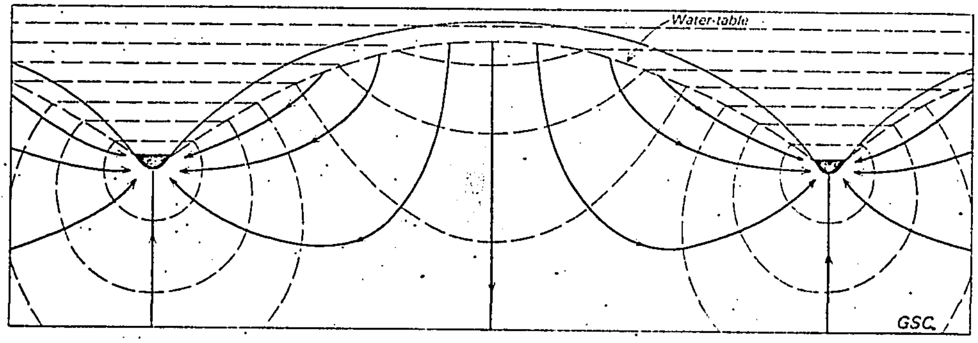


FIGURE 4 Approximate flow pattern in uniformly permeable material between the sources distributed over the air-water interface and the valley sinks (after Hubbert, 1940).

and sinks are given by $\emptyset = gz$. Below the water table, water moves from regions of high potential towards regions of low fluid potential, on a path perpendicular to the equipotential surfaces. Water enters the flow system at the free water surface and initially moves downward at some angle greater than the slope of that surface. According to Hubbert's flow pattern, recharge takes place everywhere along the surface and discharge is limited to the bottom of the valleys.

From this model, it was believed that the groundwater discharge in the river valleys was a reliable estimate of all groundwater flow in a particular drainage basin, implying that surface water divide coincides with groundwater divide everywhere (Meyboon 1967). In cases of simple topographic configuration (i.e. high area with an adjacent low) this concept was used as a model in Western Canada (Meneley 1963). A decrease in hydraulic head with increasing depth in the area of topographic highs was confirmed by field investigations, but in the areas of topographic lows, the relationship between hydraulic head and depth, incongruities were observed (Toth 1962) which suggested that Hubbert's model was incomplete.

These seeds of the present thought somehow could not take root at least for 20 years after Hubbert's paper was published in the rank and file of the profession.

4. THEORETICAL ANALYSIS IN HOMOGENEOUS ISOTROPIC MEDIUM

In 1962 Toth calculated a somewhat complicated flow model for ground water flow in a small drainage basin. He defined drainage basin as "An area bounded by topographic highs, its lowest part being occupied by an impounded body of surface water or by an outlet of a relatively low order stream and having similar physicochemical conditions over the whole of its surface".

Toth calculated flow model by considering one side of the valley as rectangular area limited by horizontal impermeable boundary at its base and two vertical impermeable boundaries extending downward from the stream and the water-divide. The potential at the water table was calculated and assuming the average water-level to be constant, Toth derived an equation for the fluid potential which satisfies both the boundary conditions and the Laplace equation.

In response to Meyboon's discussion (1962), Toth described that validity of his concept is dependent on the fulfillment of the following conditions:

(1) The basin is underlain by impermeable boundary

(2) The two valley flanks are parallel and symmetrical relative to the stream.

(3) The water table is a subdued replica of the topography.

(4) The geology is homogeneous and isotropic in the basin.

Toth's analysis accounted for local topographic relief and the resulting potential distribution differs significantly from Hubbert's model. Toth's potential distribution yielded a local flow system, an intermediate flow system and a regional flow system (Figure 5).

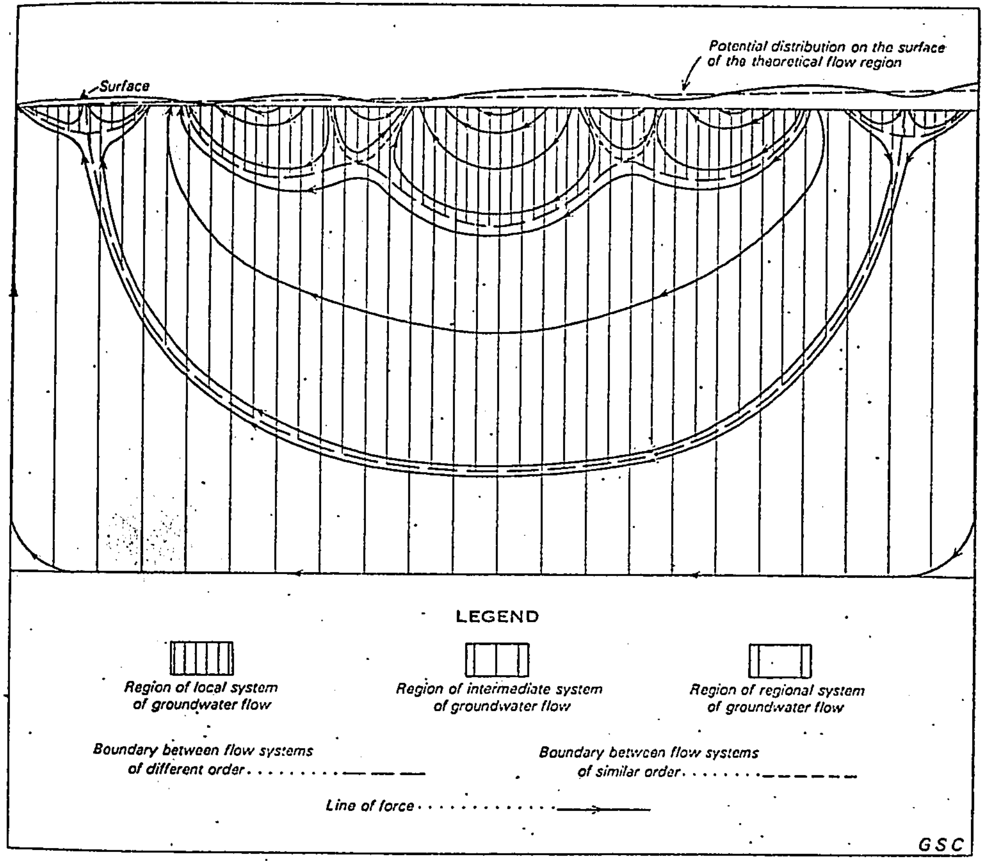


FIGURE 5 Theoretical flow pattern in a small drainage basin underlain by an impermeable boundary (after Tóth, 1962).

In determining the effect of the water table configuration on a regional flow pattern, Toth considered two cases: a constant gentle regional slope and a water table with the configuration of a sine curve, such as one must expect in a hummocky terrain. He also showed the effect of the general slope and local relief and the effect of varying the "depth: lateral extent" ratio, on the flow. By far the most important difference between Hubbert's model and Toth's model is that, in the latter, groundwater discharge is not limited to the river valley, but "the bulk of the discharge takes place between the midline and the valley bottom", where the midline is defined as "the line located on the surface midway between and parallel to the valley bottom and the water divide".

5. MODEL BASED ON OBSERVATIONS

Almost at the same time when Toth approached the problem of groundwater flow in a drainage basin by applying theoretical analysis, Peter Meyboon (1962) approached the problem by observations and field measurements of the flow in a stratified medium. Toth assumed boundary conditions and computed flow pattern and thereby inferred observable phenomena. Contrary to that Meyboon inferred the nature of groundwater flow and type of boundaries by limiting the flow region on the basis of observations and measurement. The groundwater flow pattern in a stratified medium consisting of poorly permeable layer overlying a permeable layer was called by Meyboon, the Prairie Profile.

The Prairie Profile (Figure 6) consisted of a central topographic high with areas of topographic low on either side. The profile is made up of two layers of different permeability, the upper layer having the lower permeability. The ratio of permeabilities is such ($K_1:K_2 = 1:10$) that the flow is essentially downward through the material of low permeability and lateral and upward through more permeable layers.

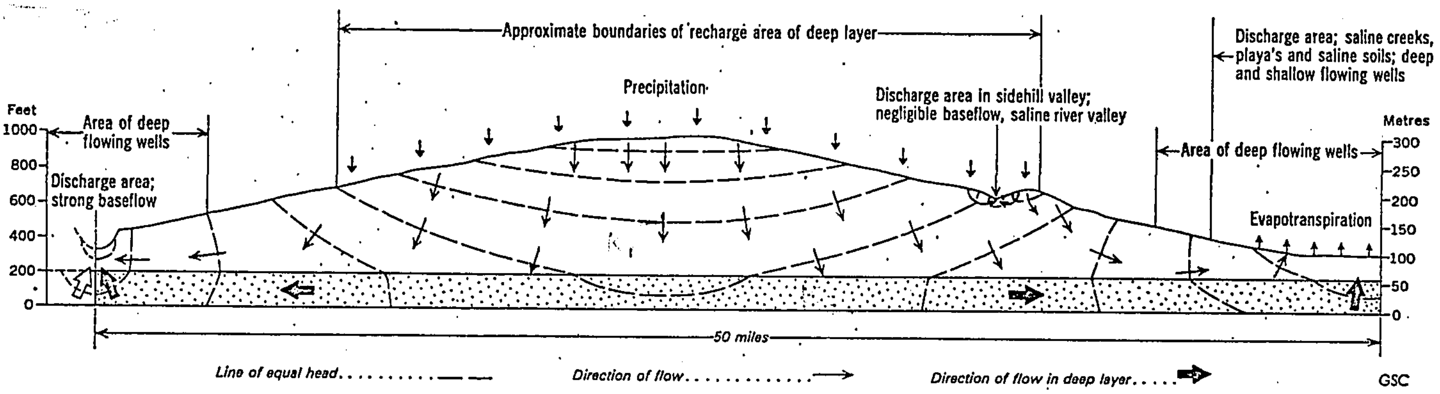


Figure 6

There are two significant points which are common in Meyboon's Prairie Profile and Toth's theoretical model. First point of agreement is that boundary conditions found by Meyboon are essentially the same as those assumed by Toth. Secondly the geology is assumed by both to be homogeneous. The more permeable layer in Meyboon's model is not intercepted by any topographic depression, therefore this feature does not affect the principal features of the flow system (Toth 1962), though deflection of groundwater in the more permeable layer is a significant feature of the Prairie Profile.

The major controversial points in both models are:

(1) Separation of recharge area and discharge area at the mid-line and lack of mechanism for removing the water from the downslope side of the midline. (Toth's theoretical model).

(2) The depth to which influence of major rivers extends and the development of large unconfined flow systems on continental scale. (Prairie Profile).

This explosion of new ideas produced by Toth, Meyboon and Ernst in 1962 put the entire matter of hydrogeology in a much wider perspective and stimulated many workers to investigate and verify the variety of complex phenomena associated with their concept of groundwater flow. Van Everdingen, Freeze and Meyboon (1966) investigated the discharge phenomena in conspicuous topographic lows in seven discharge areas in Saskatchewan and Manitoba. A spectacularly large circulation system in the southern and eastern Nevada was outlined by Eakin (1966). A large-scale cross-sectional recharge to Dakota artesian system was investigated by Swenson (1966). Roz Kowski (1969) used hydrochemical principles to confirm the flow system of Moose Mountain outlined initially by Meyboon.

6. NON-HOMOGENEOUS AND ANISOTROPIC MEDIUM

As opposed to Toth (1962, 1963), who used analytical solution to study the groundwater flow pattern in a two-dimensional, homogeneous isotropic basin, Freeze and Witherspoon (1966) using numerical methods developed a mathematical model which represents steady state regional groundwater flow in a three-dimensional, non-homogeneous, anisotropic basin.

The assumptions made about the horizontal and vertical impermeable boundaries are the same as in Toth's model. The diagrams presented by Toth were designed to show the effect of changes in "depth : lateral extent" ratio. Whereas Freeze and Witherspoon chose a fixed basin size (1:12) and instead showed the effect of changes in water table configuration.

In order to demonstrate the versatility of numerical method Freeze and Witherspoon investigated the effect of more irregular water table configurations in a homogeneous and isotropic medium as well (Figure 7).

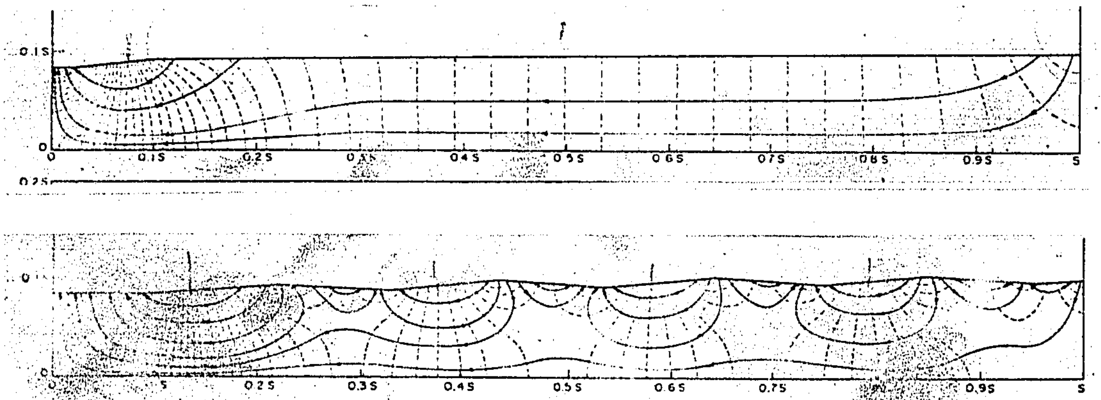


Fig. 7 Effect of water-table configuration on regional groundwater flow through homogeneous isotropic mediums.

Toth (1962) showed that in homogeneous medium with gentle water table slope, recharge is concentrated at the upstream end and discharge at the downstream end with hinge line at the mid-point. By contrast, Figure 7 shows that when a major valley is present hinge line occurs midway up the steep valley flank. Discharge is concentrated in the valley and recharge occurs over the entire upland area but is concentrated at the upstream end and at the break in slope above the valley flank.

The factors that affect the flow patterns are:

(a) "Depth : lateral extent" ratio,

(b) Water table configuration, and

(c) The stratigraphy and variations in permeability.

The permeability is a property of the medium within a region which affects the nature of the potential field. Freeze and Witherspoon examined the effect of inhomogeneity and anisotrophy of permeability on groundwater flow pattern (Figure 8).

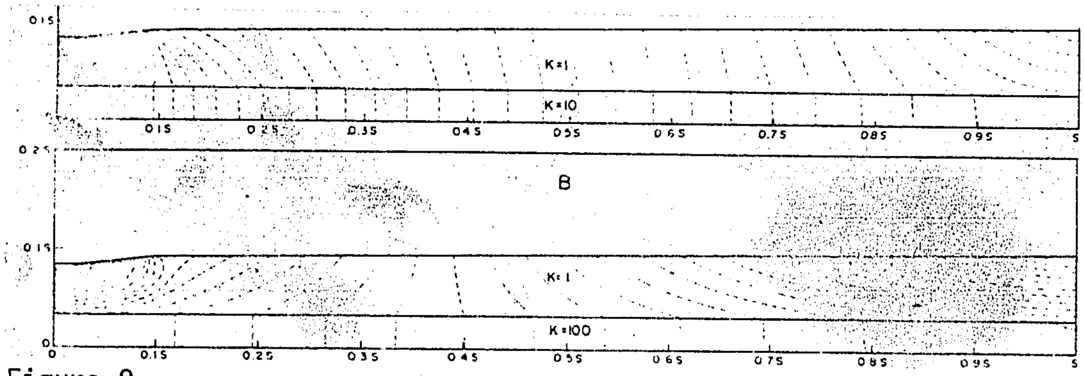


Figure 8

The effect of introducing the high permeability aquifer creates a highway of groundwater flow. As the permeability ratio increases, the vertical (upward or downward) flow through the overlying low permeability layer becomes more pronounced and the hinge-line moves upslope creating large discharge areas.

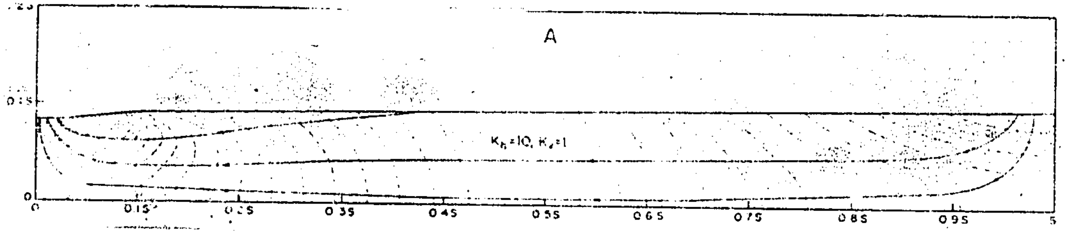


Figure 9

The effect of varying the anisotropic ratio in a homogeneous region is identical to varying the "depth : lateral extent" ratio (Figure 9).

On the other hand discontinuities (partial layers, lenses and sloping beds) result in the formation of small sub-basins which did not exist in the homogeneous case (Figure 10).

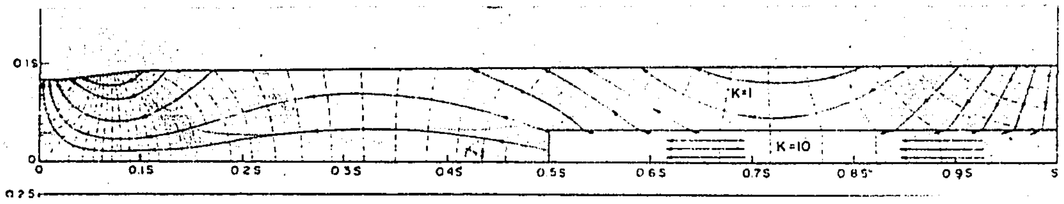


Figure 10

Therefore, from Freeze and Witherspoon's study the following important conclusions can be drawn:

(1) The groundwater discharge tends to concentrate in major valleys.

(2) In hummocky terrain, numerous sub-basins are superimposed on the regional system.

(3) Recharge areas are invariably larger than discharge areas.

(4) The buried aquifers tend to concentrate flow towards the principal discharge areas.

(5) The stratigraphic discontinuities can lead to the distribution of recharge and discharge areas that are difficult to anticipate and that are largely independent of water table configuration.

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