Fisheries and Environment Canada
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Piezometric Head in the Disposal Formation and Groundwater Chemistry of the Shallow Aquifer

A. Vandenberg, D.W. Lawson, J.E. Charron and B. Novakovic

TECHNICAL BULLETIN NO. 90
(Résumé en français)

INLAND WATERS DIRECTORATE,
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Preface

The investigation described in this report was initiated as a co-operative venture between Environment Canada and the Ontario Ministries of the Environment and of Natural Resources. The objectives and scope of the study were decided upon by mutual consultation, and progress made was discussed periodically at meetings between representatives of these agencies. Although the research aspects and field studies were primarily the responsibility of Environment Canada's Inland Waters Directorate, the investigation would not have been possible without the availability of abundant subsurface information from the files of both Ontario ministries. Provincial staff contributed immeasurably as well in the final stages of report preparation, editing and review; the names of D.D. McLean, Ministry of Natural Resources, and D.N. Jeffs, K. Goff, R.C. Hore and E. Turner, Ministry of the Environment, should be cited particularly in this respect. It is our hope that this combined input from federal scientists with the opportunity to conduct intensive field-oriented research and provincial engineers and scientists with their intimate personal knowledge of the engineering and hydrogeologic aspects of subsurface disposal in southwestern Ontario has resulted in a lasting and useful contribution to this important problem area.

Abstract

This report describes the results of a reconnaissance study on the effects of the disposal of liquid industrial wastes through wells into the subsurface of southwestern Ontario. The study was based primarily on the analysis of existing data concerning oil and gas wells, disposal wells, and water wells in Lambton County. A second important component of the study was a field survey and ground-water sampling program to help determine the chemistry and motion of shallow groundwaters in the County. It was hoped that the investigation of shallow groundwaters would provide some direct or indirect evidence for the effects of disposal at greater depths.

Drilling records from oil and gas wells in Lambton County were computer processed to map the geological structure and the piezometric head in the disposal zone near the contact of the Dundee Formation and the Detroit River Group. The geological maps were in good agreement with the known geology of the area. Since there was considerable uncertainty about the exact location of the disposal zones within the 270 feet of the Lucas Formation and the validity of the piezometric data, a series of piezometric maps was prepared based on different subsets of the data base for the disposal interval. This uncertainty was made more evident by inconsistencies in the piezometric maps for the different data subsets. Several features of the resulting piezometric surface persisted, however, through all or most of the maps, and are therefore believed to be elements of the true piezometric surface. These persistent features are displayed in a final composite map, which exhibits a regional westerly dip; hence, the regional motion of groundwater in the disposal interval is in that direction.

The major fresh water aquifer in the County is located at the bedrock-overburden contact. Its chemical water types and the data concerning its piezometric surface combine to show the direction of groundwater movement. It is suspected that a number of chemical samples, characterized by high chloride and total dissolved solids concentrations, and not entirely fitting into the regional pattern of chemical water types are indicative of contamination of the fresh-water aquifer by deep formation water. Waters of anomalous chemical type appear to be associated with low trends on the piezometric map of the disposal zone or with deep-seated geological structures or both. The deep-seated geological structures might be associated with reefs or basement features and would presumably lead to zones of higher-than-average vertical permeability crossing a number of formations.

The evidence for occurrences of chemically anomalous water is based on a limited number of samples in all cases. The actual existence of these zones must be tested by additional and repeat sampling and all possible sources of contamination reviewed. If their existence is verified, and they appear to be unrelated to surface sources of contamination, a drilling program could be considered to determine the nature of the subcropping bedrock and provide further information on the causes of the anomalies.

Development of a waste movement simulation model for the disposal zone could be visualized as the ultimate objective of deep-well disposal studies in southwestern Ontario. Unfortunately, the available information for the disposal zone is simply not adequate for this purpose. Permeability data, in particular, are required for the development of a sophisticated simulation model.

Résumé

Le présent rapport décrit les résultats d'une étude préliminaire sur les répercussions que peut avoir le rejet de déchets industriels dans des puits, à partir desquels ils s'infiltrent dans le sous-sol, dans le sud-ouest de l'Ontario. L'étude est fondée, en premier lieu, sur l'analyse des données existantes relatives aux puits de pétrole et de gaz, aux puits de refoulement et aux puits d'eau du comté de Lambton. Un second élément important de l'étude a trait aux relevés sur le terrain et à l'échantillonnage des eaux souterraines pour déterminer la chimie et le déplacement des eaux souterraines peu profondes du comté. L'étude des eaux souterraines peu profondes devait permettre d'obtenir des indices directs ou indirects des conséquences du rejet de déchets liquides à de plus grandes profondeurs.

Les rapports de sondage provenant des puits de gaz et de pétrole du comté de Lambton ont dû être traités par ordinateur, de manière à cartographier la structure géologique et la charge piézométrique dans la zone de rejet des résidus, près du contact de la formation de Dundee et du groupe de la rivière Detroit. Les cartes géologiques présentaient une bonne concordance avec la géologie connue de la région. Étant donné que les données sur l'emplacement exact des zones de rejet dans les 270 pieds de la formation de Lucas, et sur la charge piézométrique étaient peu précises, il a été nécessaire de dresser une série de cartes piézométriques, fondées sur divers sous-ensembles de la base de données relative à l'intervalle de rejet. Cette imprécision était accentuée par les incompatibilités que présentaient les cartes piézométriques par rapport aux divers sous-ensembles de données. Toutefois, la surface piézométrique ainsi construite a conservé plusieurs traits caractéristiques, dans pratiquement toutes les cartes; par conséquent, ces traits doivent constituer des éléments de la surface piézométrique réelle. Ces caractères persistants sont exposés dans une carte composite finale, qui révèle un pendage régional dirigé vers l'ouest; le mouvement régional des eaux souterraines, dans l'intervalle de rejet, suit donc cette direction.

Le principal aquifère d'eau douce du comté est situé au contact entre la roche de fond et la couverture. Les variétés chimiques d'eau et les données concernant sa surface piézométrique fournissent la direction du déplacement des eaux souterraines. Un certain nombre d'échantillons chimiques, caractérisés par de fortes teneurs en chlorures et en matières dissoutes et ne coïncidant pas entièrement avec le cadre régional des types chimiques d'eau, suggèrent que la contamination de l'aquifère d'eau douce provient des eaux des formations profondes. Les eaux de type chimique anormal semblent être associées à certaines tendances peu prononçées qui apparaissent sur la carte piézométrique de la zone de rejet, ou à des structures géologiques profondes, ou aux deux. Il est possible que les structures géologiques profondes soient associées à des récifs ou à des irrégularités du soubassement et qu'elles créent des zones de perméabilité verticale supérieure à la moyenne traversant un certain nombre de formations.

Dans tous les cas, les preuves de la présence d'eau à caractère chimique anormal sont basées sur un nombre restreint d'échantillons. Il faut vérifier l'existence de telles zones, en effectuant des échantillonnages supplémentaires et en les répétant, et en examinant toutes les sources éventuelles de contamination. Si leur existence est prouvée, et si elles ne semblent pas être liées à des sources superficielles de contamination, un programme de forage pourrait être envisagé pour déterminer la nature de la roche de fond sous-jacente et donner plus d'information sur les causes des anomalies.

Il est possible de considérer l'établissement d'un modèle de simulation du mouvement des déchets dans la zone de rejet, comme l'objectif principal des études de rejet dans des puits profonds, au sud-ouest de l'Ontario. Malheureusement, l'information disponible sur la zone de rejet est insuffisante. Il faut obtenir en particulier des données sur la perméabilité, afin d'établir un modèle de simulation perfectionné.

Introduction

The ever-accelerating pace of growth, urbanization and industrialization in Canada has been accompanied by a corresponding increase in the volume and variety of wastes. Many of these can be recycled or converted into useful by-products or into less objectionable waste types at reasonable cost; others, however, because of such factors as high costs, lack of technology or inadequate regulation, are commonly released to the environment. There they may contaminate our soils, the air we breathe, and the water we drink.

Governments at all levels in Canada and elsewhere have become increasingly aware of the threats posed to our well-being and way of life by the indiscriminate or careless disposal of industrial and other wastes. Government legislation and regulation are placing greater and greater restrictions on the intentional release of contaminants directly onto the ground or into the atmosphere or surface waters. Similarly, greater governmental control is being exercised to prevent accidental releases of contaminants to the environment and to ensure that swift effective action is taken to minimize the effects of accidents when they do occur.

These measures have had undeniably beneficial results. They have, first of all, tended to reduce or eliminate many of the more obvious pollution problems that characterize those portions of the environment that are open to public scrutiny. Secondly, there is little doubt that they have led to a reduction in the total percentage of waste materials that find their way to the environment as a whole. Despite these beneficial results, however, there is good reason to believe that there has been at least one unfortunate consequence of our efforts to clean up the visible environment. This is the increasing contamination of the earth beneath our feet from the surface down to considerable depths.

Subsurface contamination may be accidental or intentional. It persists because it is out of sight and because, in many cases, it is discovered only by accident (Miller, 1974), by which time it may be very difficult or impossible to rectify. Accidental contamination can result from surface spills, underground rupture of buried tanks and pipelines, and infiltration from surface sources such as tailing ponds, disposal pits, sanitary landfills, open-pit mine workings, etc. An example of intentional subsurface disposal is deep-well disposal of industrial wastes (van Everdingen and Freeze, 1971).

As suggested above, subsurface contamination is a rapidly growing pollution problem because it seems to present an economically advantageous alternative for getting rid of those wastes which can no longer be readily disposed of above ground. It has the considerable attraction not only of removing the wastes from view but also of making them difficult to detect. The end result is that more and more industrial and other wastes are slowly but surely making their way underground, contaminating our soils, rock strata and groundwaters. In this situation, it is, of course, important that there should be effective controls over the entry of wastes into the subsurface and their subsequent migration through the ground. There is also a pressing need for a better understanding of the phenomena that control the movement of wastes in the subsurface, including those physical, chemical and biological factors that alter the nature of the contaminants or tend to make them migrate at rates that differ from those of the subsurface waters that carry them.

THE SUBSURFACE CONTAMINATION RESEARCH PROGRAM

The Hydrology Research Division in 1970 formally initiated a program to investigate questions of subsurface contamination and to study those phenomena that affect the spread of contaminants through the subsurface. A major initial effort under this program was an appraisal of the existing situation with respect to deep-well disposal in Canada (van Everdingen and Freeze, 1971) and the preparation of publications dealing with disposal-formation and injection-well hydraulics (van Everdingen, 1974a) and the suitability of different areas and geologic formations in Canada for deep-well disposal (van Everdingen, 1974b). Some effort has also been directed towards the development of specialized instrumentation for *in situ* sampling and analysis of formation waters.

The initial objectives of the Subsurface Contamination Research Program were five in number:

1. Collection of background data for evaluation of subsurface waste-disposal potential in Canada.

2. Extension of understanding of physical and chemical processes involved in the movement and behaviour of waste material after injection into the subsurface.
3. Development of rational guidelines and quantitative criteria for use in the regulation and control of subsurface disposal of waste.
4. Development of methods for the monitoring of the movement and behaviour of injected waste.
5. Development of techniques for the prediction of movement and behaviour of injected waste.

It is apparent that these objectives were slanted towards the special case of deep-well disposal. Some of them have been realized, at least in part, through the series of publications by van Everdingen and Freeze already mentioned. Full realization, however, requires field studies as well. An excellent area for such a study is Lambton County and adjacent areas in southwestern Ontario. Here is where the bulk of Canadian deep-well disposal has taken place (McLean, 1968; van Everdingen and Freeze, 1971). The area has a relatively long history of disposal at relatively shallow depths which perhaps increases the chances of observing its effects. There are, furthermore, a number of interesting aspects to the study area, including the presence of many abandoned oil wells and the anomalous behaviour of a number of the disposal zones. Finally, there have been indications that the effects of disposal have been observed at points well removed from the disposal sites.

It was, therefore, concluded that this area of southwestern Ontario would be a fruitful one for a field study of the effects of deep-well disposal on the water chemistry of shallow aquifers. This field study was initiated in the summer of 1972 as part of the Subsurface Contamination Research Program. In addition to the field study, there was also an extensive review and analysis of water-well and oil-field information for the area. These existing data were obtained from the files of the Ontario Ministries of the Environment and of Natural Resources. They proved invaluable in assessing the hydrogeology and hydrogeochemistry of the study area. The over-all study formed part of a cooperative program of investigation in which both of these Ontario ministries have been involved.

GEOLOGY OF SOUTHWESTERN ONTARIO

The subsurface Paleozoic stratigraphy of southern Ontario has been discussed in a number of reports. A detailed bibliography of these is given by Beards (1967). The structural features of southwestern Ontario have been described by Brigham (1971). The reader is referred to these publications or to McLean (1968) or to Smith (1973) for more detailed information on the geology of the study area.

For the purposes of this report, the geologic sequence is summarized in the stratigraphic column which is shown in Table 3. The disposal zone in southwestern Ontario is the Lucas Formation consisting of dolomite with minor anhydrite beds in the lower part of the formation. In Lambton County its thickness ranges from 300 feet in the north to 200 feet in the south (Fig. 9); the top of the formation dips westward from an elevation of 300 feet above mean sea level on the eastern boundary of the county to 100 feet below sea level on its western boundary (Fig. 5).

SUBSURFACE WASTE DISPOSAL IN SOUTHWESTERN ONTARIO

In southwestern Ontario subsurface disposal of liquid wastes has been practised by industry since 1958. As the amount of toxic industrial waste increased with increasing industrialization, the public became more aware of the threat of pollution of fresh water resources, both at the surface and underground, and all waste disposal methods came under close scrutiny.

In deep-well disposal operations it is generally presumed that the subsurface conditions in the disposal area are such that the waste will remain confined within the disposal zone. Van Everdingen and Freeze (1971) list criteria for the selection of disposal formations and sites, of which the following are specifically pertinent to southwestern Ontario:

1. The disposal formation should be "homogeneous" (without high-permeability lenses or streaks) to prevent extensive fingering of waste;
2. No unplugged or improperly abandoned wells should penetrate the disposal formation in the vicinity of the disposal site, as this could lead to contamination of other resources;
3. The vertical component of the hydrodynamic gradient should be negligible or directed downward to prevent upward movement of the waste;
4. Lateral movement under natural conditions should be slow, to prevent rapid movement of the waste to a natural discharge area.

There is evidence to suggest that criteria 1 and 2 are not always met in southwestern Ontario (van Everdingen and Freeze, 1971; McLean, 1968; Beatty, 1971; Smith, 1973).

PURPOSE AND SCOPE OF REPORT

In view of the potential hazards of waste disposal in the relatively shallow Dundee Formation and Detroit River Group, the Hydrology Research Division of Environment Canada, the Water Quantity Management Branch of the Ontario Ministry of the Environment, and the Petroleum Resources Section of the Ontario Ministry of Natural Resources undertook a joint federal-provincial study of the disposal operation in order (1) to develop techniques for studying and monitoring the movement of wastes underground and (2) to document a Canadian case history of the practice.

As part of the joint study, the Hydrology Research Division let a contract to the University of Waterloo for the construction of a finite element model of liquid waste movement in a nonhomogeneous groundwater system. The model was to be applied to some hydrogeologic anomalies in the disposal zone in southwestern Ontario. This part of the study has been completed as a M.Sc. thesis (Smith, 1973). As part of the thesis study, Smith reviewed existing information on southwestern Ontario waste injection wells on file at the Ontario Ministry of Natural Resources. He examined the results of injectivity tests and spinner surveys. He concluded that the injectivity tests yielded inconclusive information on the injection zone but had no comments on the spinner survey data.

Secondly, the Hydrology Research Division undertook to be the lead agency in the analysis of the records of oil and gas wells on file at the Ontario Ministry of Natural Resources, in the preparation of maps of the disposal zone and its piezometric head, and in an attempt at an interpretation with regard to the movement of the injected waste. The study was limited to Lambton County (Fig. 1), where all of the industrial waste disposal wells in Ontario are located. A similar analysis and evaluation, also limited to Lambton County, was made of the water well records on file at the Ontario Ministry of the Environment. A related field investigation was carried out in the summer of 1972. The field investigation was concerned principally with shallow groundwater flow systems and their water quality. It had two specific objectives. These were to use hydrochemical maps of the study area

1. to indicate the directions of groundwater flow, and
2. to provide information on the hydrochemical effects of deep-well injection of brines and industrial wastes on the shallow aquifer.

It is the regional analysis phase of the joint study which forms the subject matter of this report.

Finally, if the regional analysis of the available data was successful, and if the data appeared to be of good quality, a model of the disposal zone would be attempted to simulate the movement of the disposal wastes. Therefore this report closes with an assessment of the validity of the data, the presentation of a generalized resultant piezometric map of the disposal zone, and a discussion of the feasibility of carrying out the model study.

Analysis of Oil and Gas Well Data

THE DATA BASE

Introduction

The data base for the production of the various maps was established by scrutinizing the 2980 available oil and gas well records for Lambton County. Of these records, 1536 contained useful information on the occurrence of water in one or more subsurface units below the bedrock-overburden contact. For each water occurrence a separate card was punched with the following data (Fig.2): the location and year of drilling of the well; the name of the formation in which the water was encountered, its thickness and the elevation of its top; the chemical water type and piezometric elevation of the water; the elevation of the water-bearing zone, and the depth of the water-bearing zone relative to the top of the formation in which it was encountered. Details concerning the data base and FORTRAN coding names are contained in Appendix A.

Thus 2473 cards, each representing a single water occurrence, were punched; an average of 1.6 occurrences per selected record. To these were added 209 cards containing geological information only, bringing the total number of cards to 2682; these cards constituted the data base for all subsequent processing.

Piezometric Data Errors

The piezometric elevation is the most critical and most important piece of information in the well record for this study, since its spatial distribution is one of the factors which determines the rate and direction of the waste movement. Unfortunately, it is at the same time the information most subject to error and to wide variation over time. There are three basic reasons for errors and variations in piezometric elevations: (1) incomplete recovery, (2) effects of well-field development, and (3) natural long-term variations.

Incomplete Recovery

To be of full value as an indicator of groundwater movement the water level must have fully recovered before being recorded. Nearly all of the wells in Ontario, however, have been drilled by the cable-tool method. With this technique, fluid levels during drilling are commonly kept lower than the piezometric surface as a result of bailing cuttings from the hole. Thus, particularly under conditions of low permeability and high piezometric head, considerable time must elapse after drilling has been completed before the water rises to its equilibrium level. Undoubtedly, even near-complete recovery is seldom obtained, simply because the operator does not wait - for what might be several days - to obtain information which is not vital to his interests.

Under natural stabilized conditions the piezometric elevation at any point in the subsurface should lie between the maximum regional water table elevation and the elevation of the lowest body of free water in the region. The deeper the observation point, the larger the area (region) that must be taken into account in arriving at an estimate of the possible range in piezometric elevation. Within the depth range of the main disposal zone in Lambton County, the minimum piezometric elevation that might reasonably be expected is the level of either Lake Erie or Lake Huron, i.e. around 570 feet above mean sea level (msl). The same reasoning suggests that a true water level equal to or lower than mean sea level should be extremely unlikely.

In the data base, however, recorded water levels below mean sea level are not uncommon and levels of less than 570 feet above mean sea level abound (see e.g. Figs. 13 to 17), a clear indication of insufficient recovery for most of the data.

Effects of Well-Field Development

Many of the wells have been drilled in already active oil or gas fields, under continuously varying conditions - wells being pumped or shut in - with each change potentially altering the piezometric head over a wide area.

Natural Long-Term Variations

Periodic fluctuations or long-term trends in the natural piezometric head distribution may be present, causing different values of head to be recorded for recoveries from the same zone at approximately the same location but in wells drilled 70 years apart.

Effect of Open-Hole Measurements

Piezometric head data on record are not to be confused with head measurements obtained from a piezometer. The latter is open only to a narrow zone of the rock, whereas the former represent averages of the heads for all water-bearing zones in the section of hole open at the time of measurement.

Since the assessment and enhancement of the piezometric data was one of the prime objectives of this phase of the study, these sources of error will be discussed further in subsequent sections of this report.

GEOLOGICAL MAPS

At this point the data were sufficiently organized to produce the geological maps.

Distribution of Data among the Formations

Figure 3 gives basic statistics on the data distribution in the form of a histogram representing the number of data cards for each of the formations or subsurface units and groups. The different shadings of the bars indicate the type of information: water occurrence and piezometric data, water occurrence data but no associated piezometric data, or formation top data only. The majority of water occurrences are in the Detroit River Group and the Dundee Formation, with a secondary occurrence in the Guelph, Salina and Bass Islands Formations.

Chiefly as a means of testing the data base and the contouring program (Calcomp, 1971) with its various options, a set of structural geology (geological contour) and isopach maps was prepared. Similar maps, also prepared by an automated plotting routine, have been published by Brigham (1971) and can be used for comparison.

Figure 4 shows the structure on the top of the Detroit River Group; a total of 984 data cards were used to construct the map. Figure 5 is the corresponding structure contour map from Brigham (1971); the outlined section corresponds to the southern half of Lambton County.

The most striking feature on both maps is the irregularity of the surface, attributed by Brigham (1971) to the presence of reefs in the underlying Guelph-Lockport Formation, collapse of strata following the leaching of salt from the underlying Salina Formation and the presence of two structural features, the Kimball-Colinville monocline and the Dawn structure. Although in some cases corresponding contour lines may have been continued or closed differently on the two maps, making the two appear slightly different, the main features on both maps are markedly similar.

Figures 6 and 7 show structure contours on the top of the Dundee Formation, produced from the Lambton County data cards and reproduced from Brigham (1971), respectively; 692 data points were used in the production of Figure 6. Figure 6 shows considerably more detail than Brigham's map, the latter being adapted to cover a much larger area. Apart from the extra detail, the contour lines follow the same general patterns; the most noticeable exception being the closed high (over 300 feet above msl) in the centre of the County, which appears only on Figure 6.

For comparison with Figure 4, the trend lines of the major structures (e.g. the Dawn structure) are reproduced in Figure 6 in exactly the same locations as in Figure 4. Although less pronounced, and in some instances slightly displaced because of the dips of the structure, the same trends exist on the top of the Dundee.

All of the isopach maps (Figs. 8, 9 and 10) show a marked increase in formation or group thickness towards the northwest, i.e. towards the Michigan Basin. The same general trend is indicated on the regional maps by Brigham (1971, Figs. 3-23 and 3-24). Local thinning of the Dundee Formation and Detroit River Group along the Dawn structure was noted by Brigham and described by him as associated with the leaching of salt from the underlying Salina Formation; the same process may have caused similar features along the Kimball-Colinville monocline and the unnamed trend east of this monocline. The collapse associated with such leaching may have produced vertical as opposed to horizontal permeability within the Detroit River Group and overlying formations.

PIEZOMETRIC MAPS

Several piezometric maps were prepared for selected intervals within the Detroit River Group - Dundee Formation. These maps are discussed and compared in an attempt to delineate the regional direction of groundwater flow in the disposal zone.

Selection of "Disposal" Zones

Figure 11 shows the distribution of the available piezometric data in the Dundee Formation and the Detroit

River Group as a function of the vertical distance between the zone in which the water was encountered and the top of the Detroit River Group. In addition, the shaded area of each column indicates the number of water encounters with salty water containing hydrogen sulphide (H_2S water), while the rest of the column indicates salty water without hydrogen sulphide (salt water).

On the basis of this histogram it was decided to produce five different maps showing piezometric head distributions for water-bearing units covering relatively narrow depth intervals. For the first map the data were restricted to the 20-foot interval, DZ1, centred on the mode at a depth of 20 feet below the top of the Detroit River Group (Fig. 11). This relatively narrow zone, it was felt, gave the best guarantee of representing a single, continuously permeable zone, and as such was expected to have more consistent values of piezometric head. The next two maps were produced from data in progressively wider intervals, DZ2 and DZ3, around the mode. Finally, the last two maps were produced from data above and below the mode, but overlapping interval DZ1 (Fig. 11); these two intervals were named DZU and DZL, respectively. Table 1 shows the intervals and the number of data points in each interval (zone) and the maps are presented in Figures 12 to 16.

The most noticeable feature of each map is the large number of local extrema. In the series DZ1, DZ2, DZ3 the number of extrema increases with the width of the zone, which may indicate that the DZ1 map is more successful in isolating data from a single hydrologic unit; however, the greater smoothness of DZ1 may only be a consequence of the smaller number of data points and should not be considered as "proof" that the extrema remaining on DZ1 are real. This correlation between the density of the data points and the number of extrema becomes obvious when a comparison is made, on each of the maps, between the southwest quadrant with its relatively high data density, and the remainder of the map area. It appears that over large portions of the map area the data are sufficiently sparse and/or variable that each new data point has the potential to yield a new extremum. Since this is a behaviour which is characteristic of pure error or of purely random data, great caution must obviously be applied in assigning any significance to the maps, especially if this would lead to making an assessment of the movement of injected waste.

Nevertheless, several regional features persist and one broad feature seems to be significant, namely the westerly dip exhibited most clearly on the DZ1 map (Fig. 12), and to a much lesser extent on the other four. In this regard the piezometric map parallels the structure contour map of the Detroit River Group (Fig. 4); in other words, the water generally rises, in the period allowed for recovery, to approximately the same height above the point at which it was encountered, i.e., the pressure is approximately constant throughout the area. The extrema of pressure head could reflect local permeability variations or variations in recovery times, and a map of the pressure head (Fig. 17) could be interpreted on this basis.

The doubts concerning the validity of the data led to a further selection of the data in an attempt to improve the reliability of the maps; the resulting maps will be discussed in the following sections.

Data from Wells Drilled since 1959

One of the most obvious criteria for further data selection is the completion date of the wells. By discarding the data from older wells, not only would the time span of the data base be shortened and thus the effect of

Table 1. Piezometric Maps of the Detroit-Dundee Disposal Zones

Figure No.	Height of the water-bearing zone relative to the top of the Detroit River Group, (feet)	Interval name	Restriction on type of water	Restriction on the year in which the well was drilled	Restriction on, or correction to the piezometric head	Number of control data
12	-30 to -11	DZ1	none	none	none	377
13	-40 to -1	DZ2	none	none	none	582
14	-50 to +9	DZ3	none	none	none	700
15	-30 to +19	DZU	none	none	none	587
16	-60 to -11	DZL	none	none	none	566
18	-30 to -11	DZ1	none	1959-1971	none	141
19	-30 to -11	DZ1	H_2S water only	none	none	312
20	-30 to -11	DZ1	salt water only	none	none	63
21	-50 to +9	DZ3	none	none	maximum value	241
22	-20 to -1	upper DZ2	none	none	none	296
23	-40 to -21	lower DZ2	none	none	none	289
24	-30 to -11	DZ1	none	none	random selection, group 1	188
25	-30 to -11	DZ1	none	none	random selection, group 2	189

variations in time reduced, but also it was felt that the later data would be more accurate. There are two reasons for this assumption: (1) more stringent government regulations concerning the quality of data collection and (2) a greater awareness in the oil and gas industry of the importance of piezometric data in the exploitation of hydrocarbon reservoirs. The year 1959 was selected as the cut-off date in consultation with the Ontario Ministry of Natural Resources, and the data were further selected from the DZ1 interval only, thus reducing the total number of data points for this map (Fig. 18) from 377 to 141. Subsequent discussions with Ministry officials (D.D. McLean, pers. comm.) have indicated that while it is correct to infer a general improvement in data quality since 1959, the quality of water-level recording probably remained virtually unaffected by this improvement until as late as 1972 or 1973. Thus, Figure 18 may not necessarily give an improved representation of the piezometric surface, except from the point of view of shortening the time base.

Comparison with Figure 12 shows that Figure 18 has a much smoother appearance as a result of the severe reduction in the number of data points. The extreme lows have been removed and only a few closed lows of less than 300 ft remain. The westerly dip persists and the north-trending troughs in the northwest and northeast quadrants have become more pronounced due to the elimination of a number of local highs; several other regional features of lesser credibility remain. The older data from the southern and western margins of the map area would appear to be erroneous.

Data Separation Based on Water Chemistry

Since differences in water chemistry might indicate that piezometric head data from different and unconnected zones were combined to produce the previous maps, the data from the DZI interval were also split on the basis of the recorded water type. Two more maps were thus produced - one for hydrogen sulphide and salt waters (Fig. 19) and one for salt waters (Fig. 20).

Comparison of the two maps is difficult, since the salt water map is based on only 63 points and necessarily yields a much smoother map than the hydrogen sulphide and salt map with 312 data points. Nevertheless, the main feature on both maps is again the westerly dip, and other similarities can be detected, for example, in the northwest quadrant of the map area. Thus, both water types are assumed to be from a common zone and the presence of hydrogen sulphide in salty water is inferred to be associated with local concentrations of gypsum and, possibly, pyrite.

Maximum Values of Piezometric Head

On the assumption that most of the data reflect only partly recovered water levels, a contour map of DZ3 (Fig. 21) was prepared based on the maximum values encountered for given specified areas. To this end the entire map area was subdivided by a square grid with elements whose sides were 2500 m (25 units) in length; from all data points inside each grid element only the point with the maximum piezometric head was retained for construction of the map. To avoid excessive smoothing the size of the grid element was established such that the selection affected only the areas of more than average density, for example, the southwest quadrant of the map area.

As expected, the procedure resulted in a smoothing of the contours along the southern and western margins of the map area and reduced the excessive extrapolation in the northeast quadrant. The average westerly dip, already weak in Figure 14 in comparison with that in the map for DZ1 (Fig.12), became much less pronounced and could even be interpreted as being directed more towards the northwest or as being flat. Thus, the regional groundwater movement could be inferred as being a very slow movement towards the northwest, that is, towards a discharge area associated with Lake Huron, or even as being essentially stagnant.

Subdivision of the Disposal Zone

With the exception of those for salt and hydrogen sulphide type waters, all the maps presented so far have been based on data with a sizable common set. In other words, the DZ2, DZ3, DZU and DZL intervals all contain the DZ1 interval, and therefore show more or less the same features. Therefore, the occurrence of similar features on all maps cannot be taken as an indication of the goodness of the data. Data quality may, however, be investigated by splitting the data for the DZ1 and DZ2 intervals and interpreting the resulting maps.

To clarify the significance of the four maps to be discussed in this section it is helpful, first of all, to consider in a general way the data set

$$x_i, y_i, z_i \ (i = 1,2.....n)$$

where the x_i and y_i are distinct values of the independent variables x and y, and the z_i are the associated values of a dependent variable z which is a continuous and reasonably regular and smooth function of x and y within the ranges of x_i and y_i. If the data set is of sufficient density and distributed reasonably evenly over the ranges of the independent variables, then any subset of the data selected independently—in the probabilistic sense—of the z_i, but of reasonable density and evenness of distribution in the xy-plane, must represent the function z(x,y), and contour maps on all such subsets must be similar to a high degree. Note that this part of the statement could also be used as a criterion for a good contouring technique.

However, if the z_i contain errors e_i, then

$$z_i = z(x_i, y_i) + e_i$$

and the different contour maps will show dissimilarities which will depend on the amount of overlap of the subsets and on the relative errors $e_i/z(x_i,y_i)$. If two or more subsets contain no common data, the dissimilarity is a measure of the relative error only, while features that persist through all maps are features of the function z(x,y).

The maps of DZ1 which were split on the basis of water chemistry showed some encouraging similarities, indicating to some extent that certain features of the maps are not due to error. This split, however, has the disadvantage of poor proportioning, with the bulk of the data being for hydrogen sulphide and salt water. To investigate the error in the data further, two other sets of split maps were prepared:

1. DZ2 split into an upper half with the height of the water encounter HWE ranging from -20 ft to -1 ft, and a lower half with HWE ranging from -40 ft to -21 ft;
2. DZ1 split into two sections of equal size by arbitrary selection. The data were taken as they occurred in the data set and alternately deposited in each of the two subsets; since the data were originally ordered by location, this selection ensured an even spread of the data in both subsets over the entire map area.

The four maps are shown in Figures 22, 23, 24 and 25; Table 4 contains the particulars for each map.

The upper and lower zones of DZ2 (Figs. 22 and 23, respectively) are decidedly dissimilar. On Figure 22 one is inclined to interpret two parallel high trends in a northwest-southeast direction. In Figure 23 these trends are shifted and admittedly obscure. A low trend can be delineated on this figure, more or less linear between the points (800, 500) and (1300, 400) and flanked by the two highs. Figure 23 exhibits the westerly dip noted in the DZ1 and other maps; whereas Figure 22 exhibits, if anything, a dip to the northwest as in Figure 21, the map of maximum piezometric elevation for DZ3. It is noteworthy that these same linear trends are also apparent in Figure 21 and that there may be a divide in the low around point (1200, 400).

The two maps resulting from the random split of the DZ1 data (Figs. 24 and 25) demonstrate that the westerly dip is a persistent feature but that it might be more accurately described as a northwest dip—as can be realized by following the main 400- and 500-ft contours. The high in the northwest corner is also persistent, as are the adjacent lows to the south and to the east. Other features—as, for example, the north-trending trough in the northwest quadrant which was so pronounced on Figure 18—are inconsistent, and must therefore be regarded as unreliable. Reconsidering the general comments which have been made above concerning the significance of the maps, it is concluded that the piezometric maps have broad regional features which can be regarded as credible. Figure 26 is a hand-crafted contour map of DZ1 and incorporates only those features which are considered to be reliable. It should be emphasized that these contours have only regional significance, are inaccurately located, and represent average values of partially recovered water levels which are lower than the true piezometric head. An analogous map for DZ2 would indicate a more gentle regional dip inclined more towards the northwest, as well as northwest linear trends and much more obscure features in the northwest quadrant. A map based on maximum values for DZ3 would be similar to the above map for DZ2 but with an even flatter dip to the northwest.

Conclusions

Despite the fact that 2980 records from wells drilled into the disposal zone in Lambton County were available, the information from them is not adequate to evaluate the hydrogeology of the disposal zone properly. The best interpretation of the data suggests that the regional groundwater movement is directed towards the northwest. The data are not adequate to draw conclusions on the direction of regional groundwater movement in the northwest quadrant, that is near Sarnia. Trend surface maps for DZ1 bring out the regional direction of groundwater movement (Fig. 27) and the features mentioned above (Figs. 28 and 29). The map of pressure head for DZ1 (Fig. 17) may reflect permeability variations, but this inference is rather shaky considering the evidence for incomplete water level recovery.

Chemistry and Motion of Shallow Groundwater

INTRODUCTION

Throughout Lambton County groundwater provides potable water for domestic and farm use. Contamination of this vital resource by accidental breakthroughs from the disposal formations is one of the prime concerns of the public (Beatty, 1971). A study of the motion and chemistry (quality) of groundwater in the overburden and the upper part of the bedrock is therefore a fitting part of this study.

Data on the availability and the source of potable groundwater have been published as a groundwater probability map (Ontario Water Resources Commission, 1969), which also gives quality data for 60 water samples from throughout the County. This chapter provides additional data and a comprehensive picture of the water chemistry in the surficial and upper bedrock deposits, including inferences as to the direction of groundwater movement and the risk of contamination. This additional information is based principally on the field survey conducted during the summer of 1972.

SOURCE OF POTABLE GROUNDWATER

Since the subcropping bedrock is, for the most part, shale of the Kettle Point Formation and limestone and shale of the Hamilton Formation (Fig. 30), it is generally unsuitable as a source of potable water; consequently, 90 per cent of the water wells are drilled into the sands and gravels directly overlying the bedrock (Ontario Water Resources Commission, 1969). Figure 31 shows the elevation of the bedrock surface and thus the elevation of the sand and gravel aquifer; Figure 32 shows the elevation to which the water in this aquifer rises (piezometric head); both maps are computer contoured from data on file at the Ontario Ministry of the Environment. Comparing these maps with the topographic contour map (Fig. 1), it is seen that on the whole both the topography and the piezometric surface follow the bedrock surface.

The picture of the aquifer which emerges is that of a thin layer of sand and gravel spread out unevenly over the bedrock surface, confined underneath by the shaly bedrock, and confined above by the clay and till which form the bulk of the overburden material (Ontario Water Resources Commission, 1969). The motion of the water is determined indirectly by the topography and is everywhere in the direction of the surface gradient. Locally, along the St. Clair River, the head in the aquifer is below stream level, and river water may infiltrate into the aquifer, most likely to move to nearby pumping wells. Locally also, groundwater may be discharging into the small creeks and streams of the area. On a regional scale, however, recharge to the aquifer occurs in the higher areas on the eastern border of the County and discharge, into the St. Clair River and Lake Huron. Thus, the deduced regional horizontal vector of groundwater motion in the bedrock disposal zone (Fig. 26) is similar to the regional horizontal vector of shallow groundwater movement; and regional movement in the disposal zone also appears to be influenced by the topography.

Unless the recorded water levels are grossly below the true piezometric head because of incomplete recovery, comparison with Figure 26 also indicates that the piezometric head in the disposal zone under natural conditions is from 200 to 300 ft below the piezometric head in the shallow aquifer; therefore water—for example, natural brines—from the disposal zone can only be expected to move into the shallow aquifer through unplugged oil and gas wells drilled many years ago or along paths of high vertical permeability when the vertical piezometric gradient is reversed by artificial causes. Waste disposal operations in Lambton County, for example, use an average injection pressure of 400 p.s.i. (McLean, 1968), equivalent to 900 ft of fresh water head.

CHEMISTRY OF SHALLOW GROUNDWATER

During the 1972 field season 102 samples were collected from wells and springs in the County and analyzed at the Water Quality Branch Laboratory of the Inland Waters Directorate. Schoeller's (1935, 1955, 1959, 1960, 1961, 1962) semilogarithmic diagrams for the major anions and cations—Ca^{++}, Mg^{++}, Na^{+}, Cl^{-}, $SO_4^{=}$, HCO_3^{-}— were drawn up for each analysis and then grouped according to the patterns which developed

(Charron, 1969). Seven distinct chemical types could be recognized:

Type A1	HCO_3^-			group A, bicarbonate-chloride waters (90 samples)
Type A2	HCO_3^-	+	Cl^-	
Type A3	Cl^-	+	HCO_3^-	
Type A4	Cl^-			
Type B1	HCO_3^-	+	SO_4^{--}	group B, bicarbonate-sulphate-chloride waters (12 samples)
Type B2	SO_4^{--}	+	Cl^-	
Type B3	Cl^-	+	SO_4^{--}	

The average composition of the waters of group A is shown by means of semilogarithmic diagrams in Figure 33. Apart from the preponderance of HCO_3^- and Cl^-, this group is further characterized by extremely low SO_4^{--} concentrations, by a Ca^{++}/Mg^{++} ratio greater than one and—except for type A4—by a negative base-exchange index (Cl^- Na^+). All constituents increase with increasing water-type number except for the bicarbonate, which changes very little between types, and for the sulphate, which decreases slightly from A3 to type A4. Combined with the steady decrease of the bicarbonate/chloride ratio, on which the division in types is based, the increases in concentration noted above indicate a progressive aging of the water from type A1 to type A4 and hence the direction of groundwater movement.

The 12 samples constituting group B (Fig. 34) are distinguished from the waters of group A by their much higher sulphate concentrations and, with the exception of type A4, by slightly higher calcium and magnesium concentrations. From type B1 to type B3 there is a steady increase in total dissolved solids and the base-exchange index, and a decrease in the bicarbonate/(sulphate plus chloride) ratio; all of which are indicative of an aging sequence and the analogous direction of groundwater movement.

The areal distribution of the 102 samples and the inferred water types are given in Figure 35. Comparing Figure 35 with the bedrock geology map (Fig. 30), it is apparent that the waters of group A are generally associated with the shale subcrops of the Kettle Point and Hamilton Formations, whereas those of group B are generally characteristic of Hamilton Formation limestone areas. Several exceptions are worthy of note, however. The tongue of A4 water northeast of Sarnia is associated with limestone and the single sample of B3 water near the southern border of the County is anomalous in that it is not associated with any known limestone subcrop. In addition, the area of A1 water associated with the Dundee limestone has been delineated on the basis of only one sample. These and other minor exceptions may be due to geochemical variations within the formations themselves, to the variability in the proportions of bedrock water and overburden water in the developed aquifer, or to the other factor controlling groundwater chemistry—the length of the flow path from the recharge area or, more correctly, the contact time with the soil and rock traversed.

The direction of groundwater motion as inferred from the chemical water types is delineated in Figure 35 and fits remarkably well with the flow system revealed by the piezometric-head map (Fig. 32). It is obvious that the tongue of A4 water mentioned above is due to the length of the flow system. Similarly, the A1 water associated with the Dundee limestone is explained by its location in a recharge area. A number of explanations can be rendered for the single anomalous occurrence of B3 water in the main A3 zone. It might be associated with downward leakage of oil field brine releases over the past 100 years or so. The simplest explanation is that it is associated with an unknown limestone subcrop, but the most interesting and consequential from the point of view of this study is that it may indicate discharge into the surficial deposits from a deeper bedrock formation, possibly even the disposal zone. In this respect it should be noted that the anomaly is closely associated with the Dawn structure (Figs. 4 and 5) and that this structure could be associated with increased vertical permeability extending as deep as the Salina salts, possibly crossing the disposal zone and traversing the thickness of the subcropping shales. This anomaly should be tested by additional and repeat sampling and all possible sources of contamination reviewed. If the anomaly is confirmed, and it appears to be unrelated to surface sources of contamination, further investigations should be contemplated. A drilling program, for example, would establish the presence or absence of a limestone subcrop.

Because of the limited number of samples of group B waters and the distribution of these few samples primarily along the east margin of the study area, this aging sequence cannot be as conclusively related to the flow of groundwater as that of group A. The meagre evidence available suggests that the group B waters along this margin are in a different flow system from the group A waters. This second system flows east and eventually heads towards Lake Erie. Local occurrences of B group waters within A group areas must therefore be related to limestone subcrops or upward groundwater movement from deeper limestone formations. Two such occurrences are in evidence on Figure 35. One (B3 type) is apparently unrelated to limestone subcrops and has already been discussed; the other (B2 type) contains lower total dissolved solids and is close to known limestone subcrops. The fact that this second occurrence contains fewer total dissolved solids and is associated with an area of known limestone subcrops lends support to the hypothesis that the anomalous B3 water already discussed may be related to discharge from deeper bedrock formations.

It is revealing to compare the features of the chemical water type map (Fig. 35) with those of the final smoothed hand-drawn piezometric map for the disposal zone (Fig. 26). The piezometric high in the northwest quadrant and its two flanking lows are mimicked by a groundwater recharge area and two associated discharge areas on the water type map. The recharge area, however, is displaced considerably to the southwest of the piezometric high. Both map types indicate a regional groundwater movement towards the west or northwest and the presence of a divide separating another flow system directed towards the east or southeast. There is a much closer correspondence, of course, between the groundwater recharge area indicated by the chemical water type map (Fig. 35) and a piezometric high for the surficial aquifer (Fig. 32). It is likely that the piezometric head in the disposal zone, although partially controlled by topographic high areas beyond the County, is also determined to a large extent by the local configuration of the water table.

So far the chloride waters (type A4) have been discussed as belonging naturally to group A; however, there are several reasons to question this assumption:

1. They occur (Fig. 35) as two isolated tongues at the extreme end of the flow system, instead of forming a continuous band along the shores of Lake Huron and the St. Clair River;
2. Whereas the sulphate concentration increases steadily from type A1 to A3 (Fig.33), it decreases between types A3 and A4;
3. Only type A4 has a positive base-exchange index. It should be noted, however, that this may only be a result of the natural trend of increasing base-exchange index that is evident throughout the sequence from A1 to A4.

Thus the chloride waters give the impression of not entirely fitting into the regional pattern and, in view of the waste disposal history of Lambton County, it seems reasonable to investigate whether leakage of formation water from the bedrock formations could be causing this type of water. The coincidence of these tongues with troughs in the piezometric surface of the disposal zone (Fig. 26) suggests the possibility that there may be leakage from the Dundee Formation and Detroit River Group. Furthermore, the tongue in the southwest quadrant is associated with the Kimball-Colinville monocline, another area of possible increased vertical permeability in the bedrock formations.

The semilogarithmic diagrams of Figure 36 present the average composition of formation waters from the Dundee Formation and the Detroit River Group, together with the corresponding diagrams for type A3 and A4 waters already displayed in Figure 33. While the average calcium, magnesium, sodium and chloride concentrations of type A4 could be derived from simple mixing of Dundee Formation or Detroit River Group type waters with water from type A3, this is not true for the sulphate and bicarbonate. It must be remembered, however, that Figure 36 deals only with average concentrations; this, plus the fact that processes other than simple mixing may be involved, suggests that the mixing of deeper waters with type A3 surficial waters may still be a viable hypothesis.

Towards the end of the study some additional data on the chemistry of the shallow groundwater were made available from two sources:

1. 22 samples from wells in the Township of Moore, collected by Lambton County Scientific Inc., on behalf of Tricil Waste Management Ltd. (Goodfellow Division), and analyzed for total solids, chloride and phenol;
2. 31 samples from the Townships of Sarnia, Moore, Sombra and Enniskillen, collected June 1973 by the Ontario Ministry of the Environment and analyzed for chloride and sulphate. The results are typical of data collected by the Ministry on a quarterly basis from 1971 to the present as part of an environmental monitoring program.

In comparing these data with the results of the 1972 field survey, it was found that 7 of the 53 samples had chloride concentrations well in excess of the average value for the set of 336 ppm. The locations of these 7 sample points are shown on Figure 35, numbered from 1 to 7 and followed by M (Ministry of Environment) or G (Goodfellow); the chloride concentrations (in parts per million) are shown in comparison with the chloride concentration at the nearest sampling point(s) of the 1972 survey (see table).

New Sample No.	Chloride (ppm)	Nearest Sample of 1972 Survey	Chloride (ppm)
1G	1160	57	332
2M	687	89, 90	792, 636
3M	835	89	792
4M	1440	30, 61, 72	1010, 1660, 2180
5M	757	27, 40	1020, 580
6M	986	27	1020
7M	706	88	792

Except for sample 1G, all chloride concentrations are comparable to those at the nearest sample locations from the 1972 survey, and if a complete analysis were available, the chemical water type would likely fit the pattern of Figure 35. The chloride concentration for sample 1G, however, is over 3 times that for sample No. 57, the nearest sample of the 1972 survey.

In summary, there is ample reason to watch these A4 areas closely in any monitoring program that might be contemplated for the subsurface disposal operations. Both the A4 areas and the B2 and B3 anomalies should be investigated further by collecting additional samples to confirm their existence and delineate their extent more accurately. The B2 and B3 areas may also require some monitoring.

Summary

The hydrogeological data available on records from oil and gas wells in Lambton County, after careful scrutiny and elimination of obviously poor data, have been used in the computer preparation of geological structure contour and isopach maps, maps of the piezometric surface of the disposal zone at the Detroit River Group-Dundee Formation contact, and a pressure head map. The geological maps are in good agreement with the existing knowledge of the area. The pressure head map may reflect regional permeability trends.

A considerable effort was made to evaluate the reliability of the piezometric data. By preparing maps based on subsets of the data, selected on the basis of such criteria as elevation above or below the Detroit River Group-Dundee Formation contact, year of drilling and quality of water, certain elements of the various surfaces so produced were found to persist. On the assumption that these persistent features reflect elements of the true piezometric surface of the disposal zone, trend surface maps and hand-drawn maps were, therefore, prepared to show the regional direction of deep groundwater movement in the disposal zone and present the persistent features. Regional groundwater movement in the disposal zone appears to be governed partially by the water table.

The second part of the report deals with the geochemistry of the water at or above the bedrock-overburden contact and its possible relationship with the groundwater in the bedrock, particularly in the bedrock subcrops and in the disposal zone. The most significant conclusions were:

1. The distribution of chemical water types indicates the same regional groundwater motion as the piezometric surface for the surficial aquifer.
2. The groundwater in the areas underlain by shale from the Kettle Point and Hamilton Formations is generally characterized by low sulphate concentrations and on the whole a lower total solids concentration than groundwater in areas underlain by limestone of the Hamilton Formation.
3. The occurrence of chloride water of relatively high total solids concentration at two locations in the discharge zone coincides with low trends in the piezometric maps of the disposal zone. One of the chloride zones coincides with the Kimball-Colinville monocline, and hence there is reason to suspect that these two features may be indicative of upward leakage from deep formations. Injection pressures used in waste disposal operations in Lambton County are sufficient to cause such upward leakage locally.
4. An anomalous occurrence of high chloride and sulphate water is associated with the Dawn structure and may also be indicative of deep leakage. The anomaly should be confirmed by additional sampling and could be further investigated.

Recommendations

The anomalous occurrence of chloride and sulphate water along the southern margin of Lambton County should be confirmed by additional sampling and all possible sources of contamination reviewed. If the anomaly is confirmed and appears to be unrelated to surface sources of contamination, a drilling program could be considered to determine whether the anomaly is related to an unknown limestone subcrop. The absence of a limestone subcrop would provide further evidence to suggest leakage from deeper bedrock formations. In this case, appropriately located wells should also be provided for monitoring any changes in groundwater quality of the overburden aquifer in these critical areas.

Monitoring of the chloride waters to the northeast and south of Sarnia should also be considered.

In view of the present state of our knowledge of the subsurface hydrogeological conditions, it is not recommended that an attempt be made at regional modelling of the flow of groundwater and the movement and spread of wastes in the disposal zone. For this higher level of refinement the piezometric data are not sufficiently reliable. Furthermore, a successful model would have to be based on a fairly accurate knowledge of the permeability of the strata; the pressure-head map (Fig.17) is considered too unreliable as a source of permeability data, and the information on hand on cores from the disposal zone or from injectivity tests appears to be too meagre. A well-conceived modelling study would require a second attempt at collecting the available information on permeability, the cooperation of industry, and the possible assistance of a reservoir engineer thoroughly familiar with the oil and gas fields of southwestern Ontario.

If such modelling is contemplated in the future, then the most logical first model would be a simple two-dimensional model of the disposal zone. Further refinements could involve vertical leakage terms in the two-dimensional model, i.e. a pseudo three-dimensional model.

Although the two-dimensional treatment of the data discussed in this report has yielded some encouraging and even remarkable results, a complete understanding of the movement of formation fluids and injected waste can only be gained if the problem is eventually considered in its full three-dimensional context.

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Figures 1 to 37

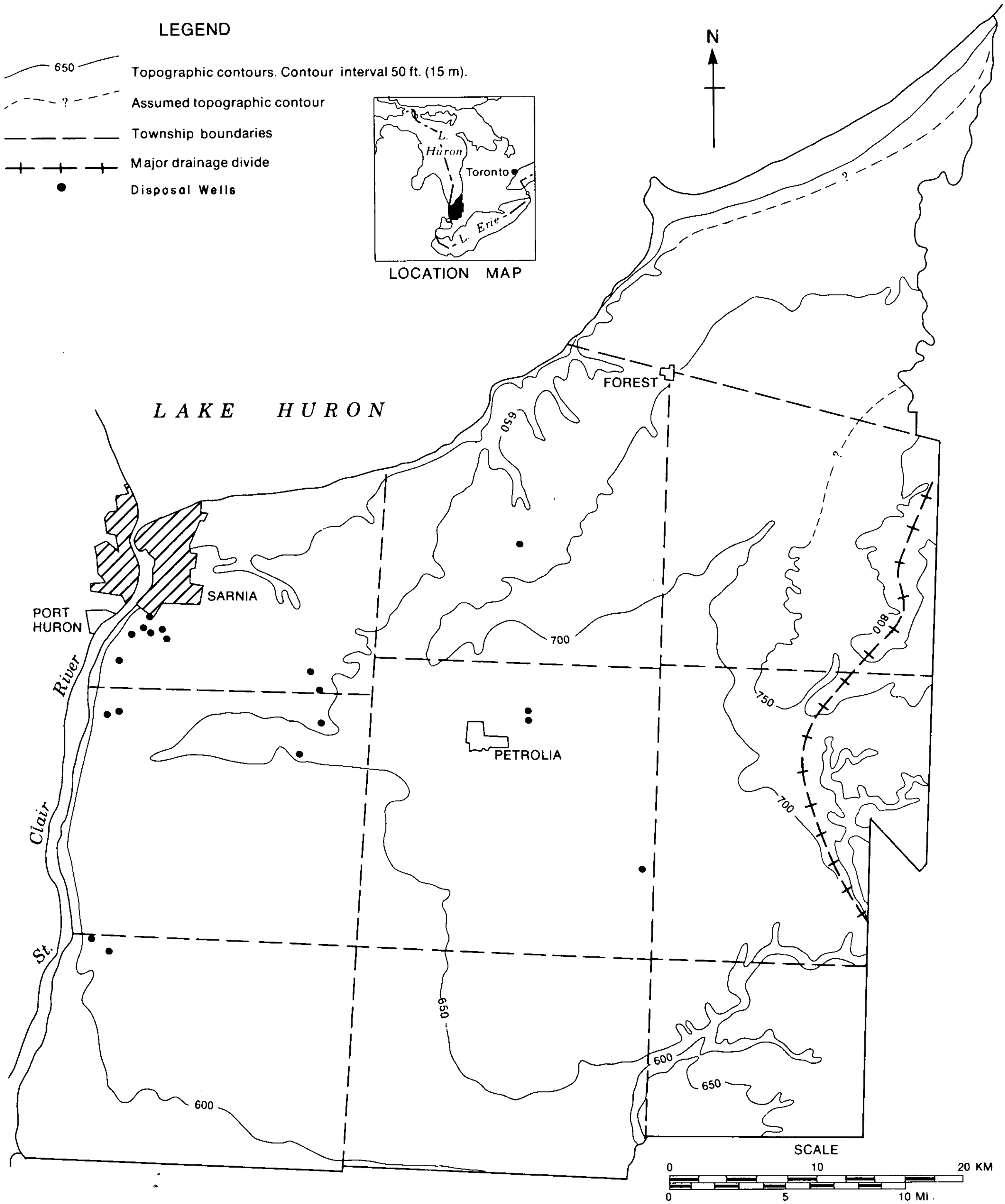

Figure 1. Map of Lambton County, showing the location of disposal wells.

CLASS: Storage | FIELD OR POOL: Seckerton | FINAL STATUS: Gas Storage

COUNTY: Lambton | TOWNSHIP: Moore | LOT: 21 | CONC: VIII

WELL NAME: Tecumseh Seckerton no. 5 | PERMIT No.: 1803

OPERATOR: Tecumseh Gas Storage Ltd., Toronto | TOTAL DEPTH: 2344 ' | P.B.T.D.:

DRILLING CO.: W.R. Kiser | Cable [ ] Rotary [x] | ELEVATION: 647 ' + 6'

GEOLOGY BY: W.B. Koepke (R/A log) | CO-ORDINATES: 530' S. of N. Lot Line, 140' W. of E. Lot Line

GEOLOGICAL CONTACTS				TOP	ELEV.	THICK.
Samples start at ft.						
Lake Level						
Drift/Lake bottom				6		124
DEVONIAN	PORT LAMBTON					
		Kettle Point		130		152
	HAMILTON			282		270
		Marcellus				
		Dundee/Delaware		552		102
	DETROIT RIVER	Lucas		654		326
		Amherstburg				
		Bois Blanc		980		186
SILURIAN		Bass Islands		1166		159
	Salina	G unit	shale	1325		931
		F unit	shale	1355		
		E unit	carb.	1595		
		D unit	salt	1686		
		C unit	shale	1720		
		B unit	marker			
			salt	1775		
			anhy.			
		A-2 unit	carb.	2035		
			salt			
			anhy.	2182		
		A-1 unit	carb.	2210		
			evap.			
		Guelph		2256	reef	89+
		Eramosa				
	AMABEL	Goat Island				
		Gasport				
		Rochester				
		Irondequoit				
		Reynales				
		Thorold				
	CATARACT	Grimsby				
		Cabot Head				
		Manitoulin				
		Whirlpool				
ORDOVICIAN		Queenston				
		Meaford-Dundas				
		Collingwood				
	TRENTON	Cobourg				
		Sherman Fall				
		Kirkfield				
	BLACK RIVER	Coboconk				
		Gull River				
		Shadow Lake				
CAMBRIAN						
PRECAMBRIAN						
Total Depth Samples ft.				2245'		

LATITUDE: 42° 51' 38''

LONGITUDE: 82° 23' 13"

SPUDDED: April 15, 1964

COMPLETED: June 4, 1964

ABANDONED:

SPL. TRAY No. 5265 - 6 | INDEX No.:

INITIAL GAS RECORD

INTERVAL	NATURAL FLOW	S.I. PRESSURE
2212 - 2216 '	901 McfD	
2257 - 2272'	4.5 MMcfD	
2293 - 2344'	19.6 MMcfD	

INITIAL OIL RECORD

INTERVAL	NATURAL FLOW	API GRAVITY
	Nil	

WATER RECORD

INTERVAL	LEV. FR. SURF.	FLOW	TYPE
138'			Fresh
680'	300'		Sulphur

CASING AND TUBING RECORD

SIZE	WEIGHT	SET AT	HOW SET	REC.
13 3/8"	54#	144'		
10 3/4"	40.5	576'		All
8 5/8"	24	1338'	Cem(420sx)	
7"	23	2210'	Cem(210sx)	

LOGGING RECORD

LOGGING CO.: WELEX | LOGGER'S T.D.: 2344'

LOGGED INTERVAL	TYPE	LOGGED INTERVAL	TYPE
2344 - 0'	R/A		
2311 - 2050'	DENL		

CORING RECORD

SIZE: | STORED:

CORED INTERVAL	REC.	ANAL.	CORED INTERVAL	REC.	ANAL.
Nil.					

REMARKS

F - Salts: - 1486-1515, 1534-1595

Dec. 16/64: acidized with 500 gal 15% HCl and 3000 gal retarded acid(64.' MMcfD flow rate)

[ ] D.S.T. (S) ON FILE (see over) | TREATMENT: [ ] (see over)

FINAL RESULTS

OIL	Nil
GAS	25 MMcfD
PRESSURE	420 psia
PRODUCING INTERVAL(S)	

PERFORATED [ ] OPEN HOLE [ ]

FORMATION(S)

YEAR: | PERMIT No.: | CONCESSION: | LOT: | TOWNSHIP: | COUNTY: | WELL NAME:

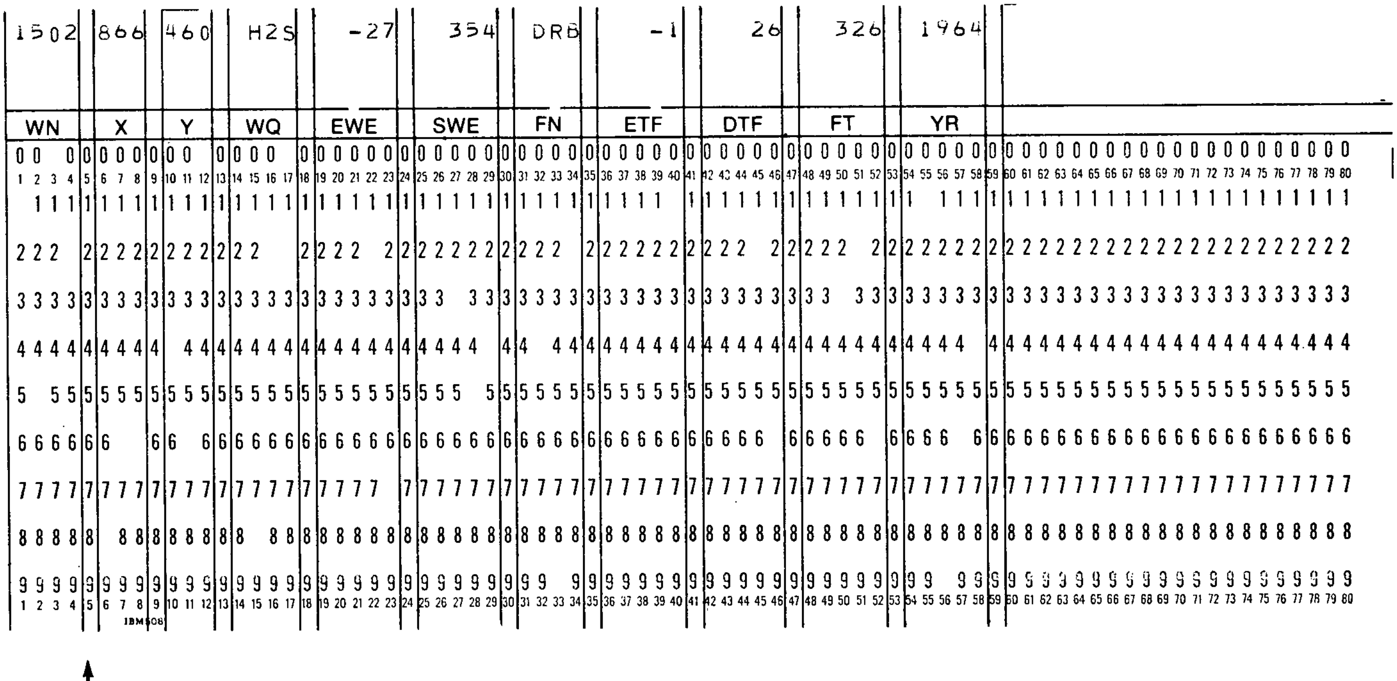

Figure 2. Typical oil and gas well record and associated computer card.

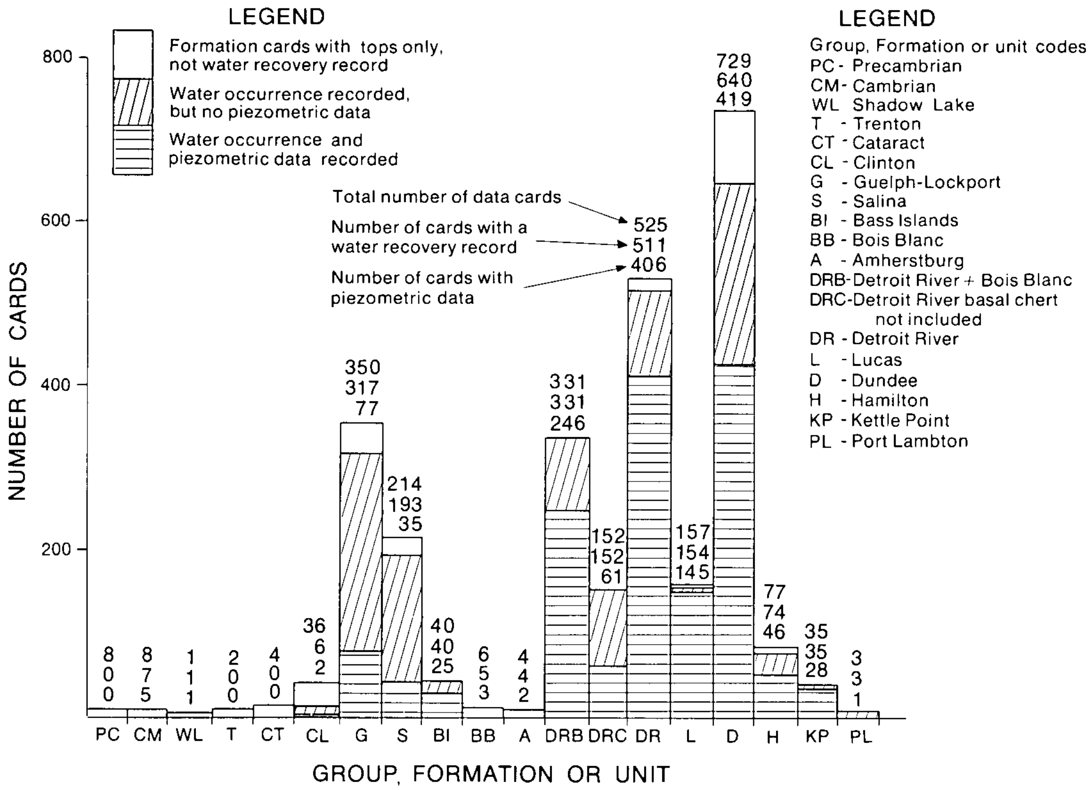

Figure 3. Amount and type of data per formation.

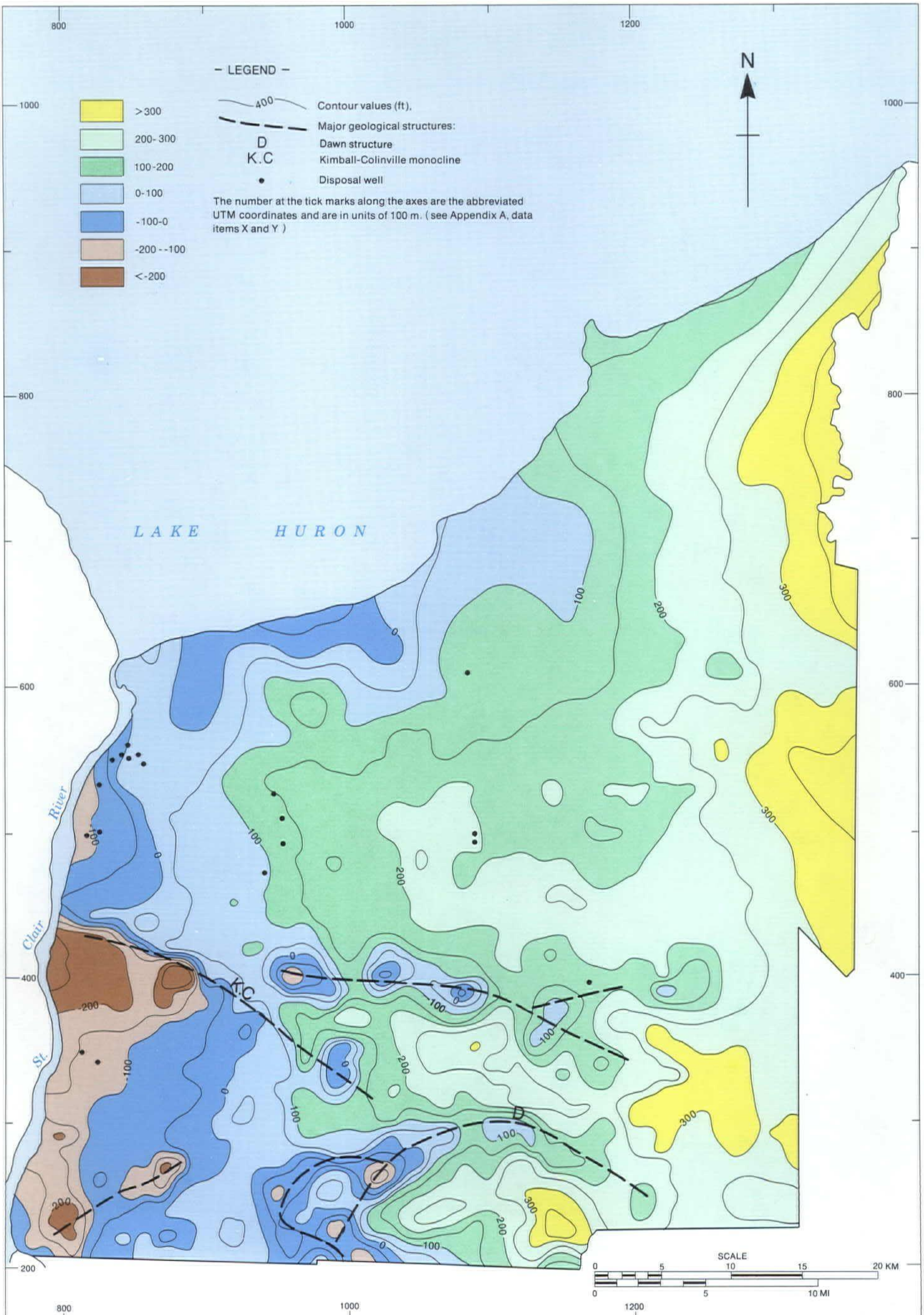

Figure 4. Structure contours on the top of the Detroit River Group.

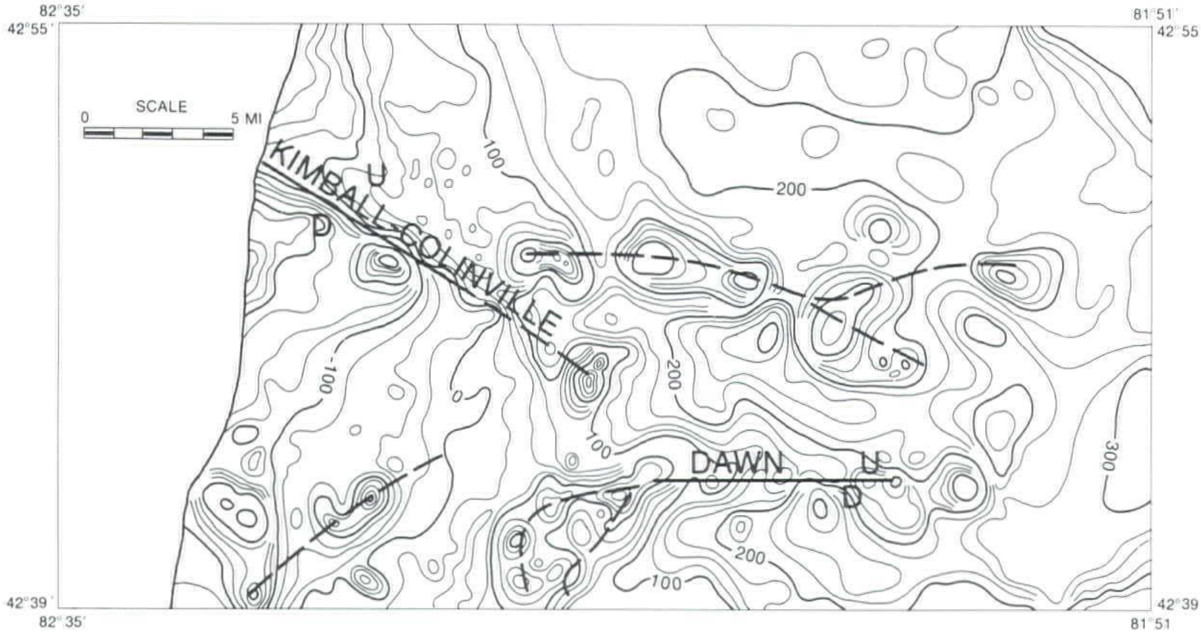

Figure 5. Structure contours on the top of the Detroit River Group, from Brigham (1971).

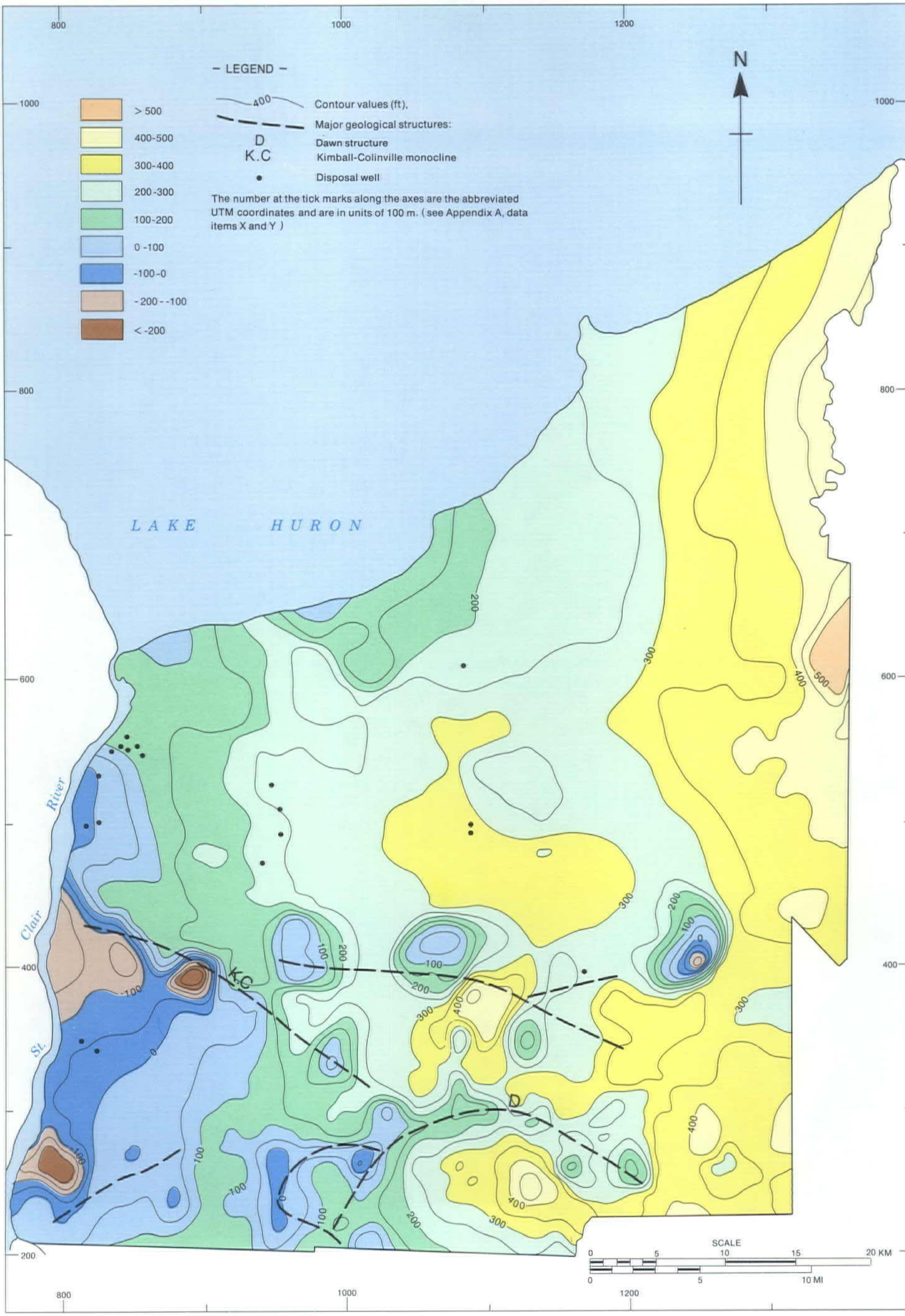

Figure 6. Structure contours on the top of the Dundee Formation.

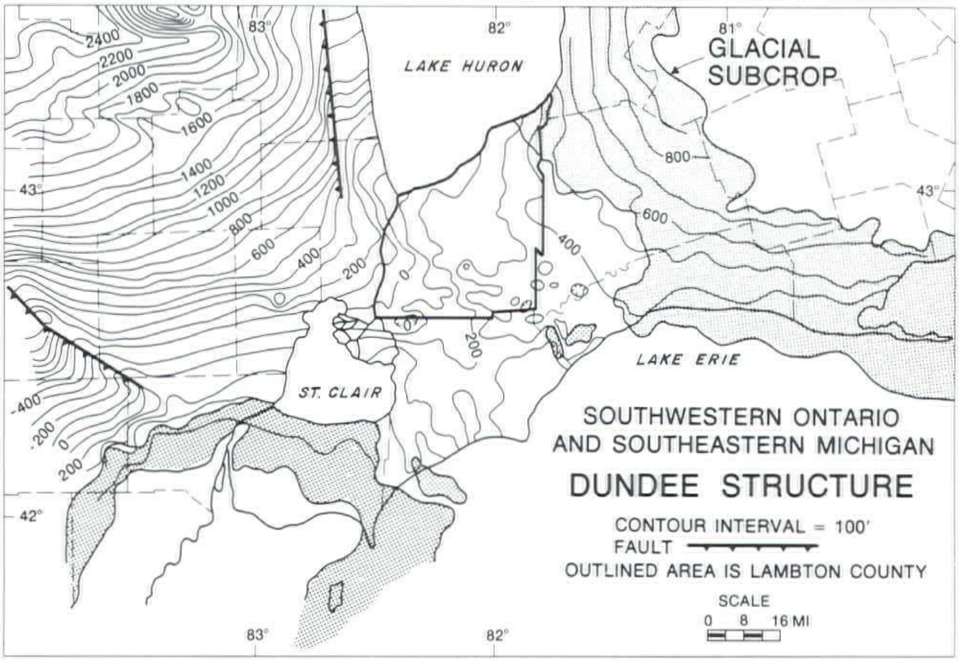

Figure 7. Structure contours on the top of the Dundee Formation, from Brigham (1971). The outlined area is Lambton County.

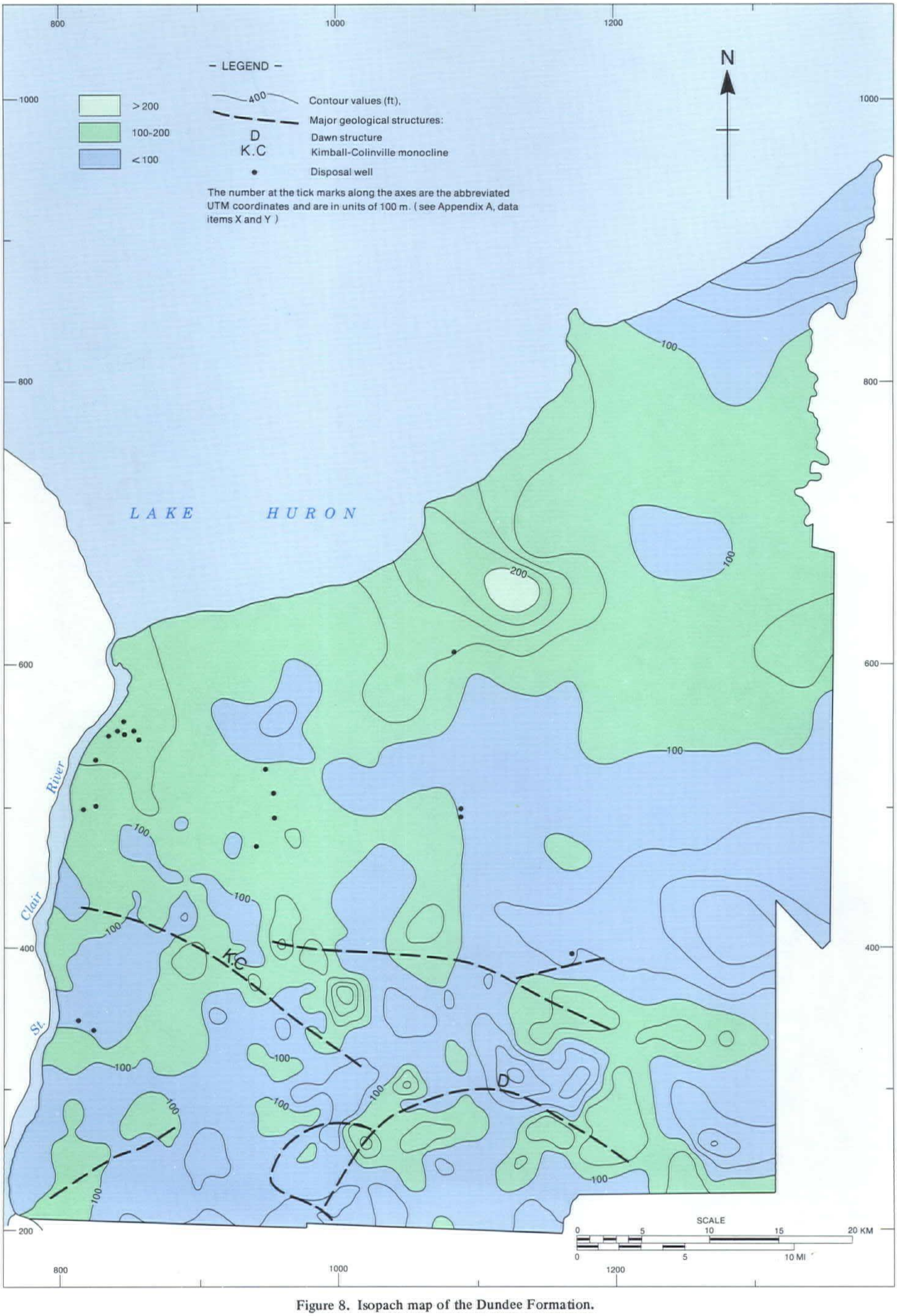

Figure 8. Isopach map of the Dundee Formation.

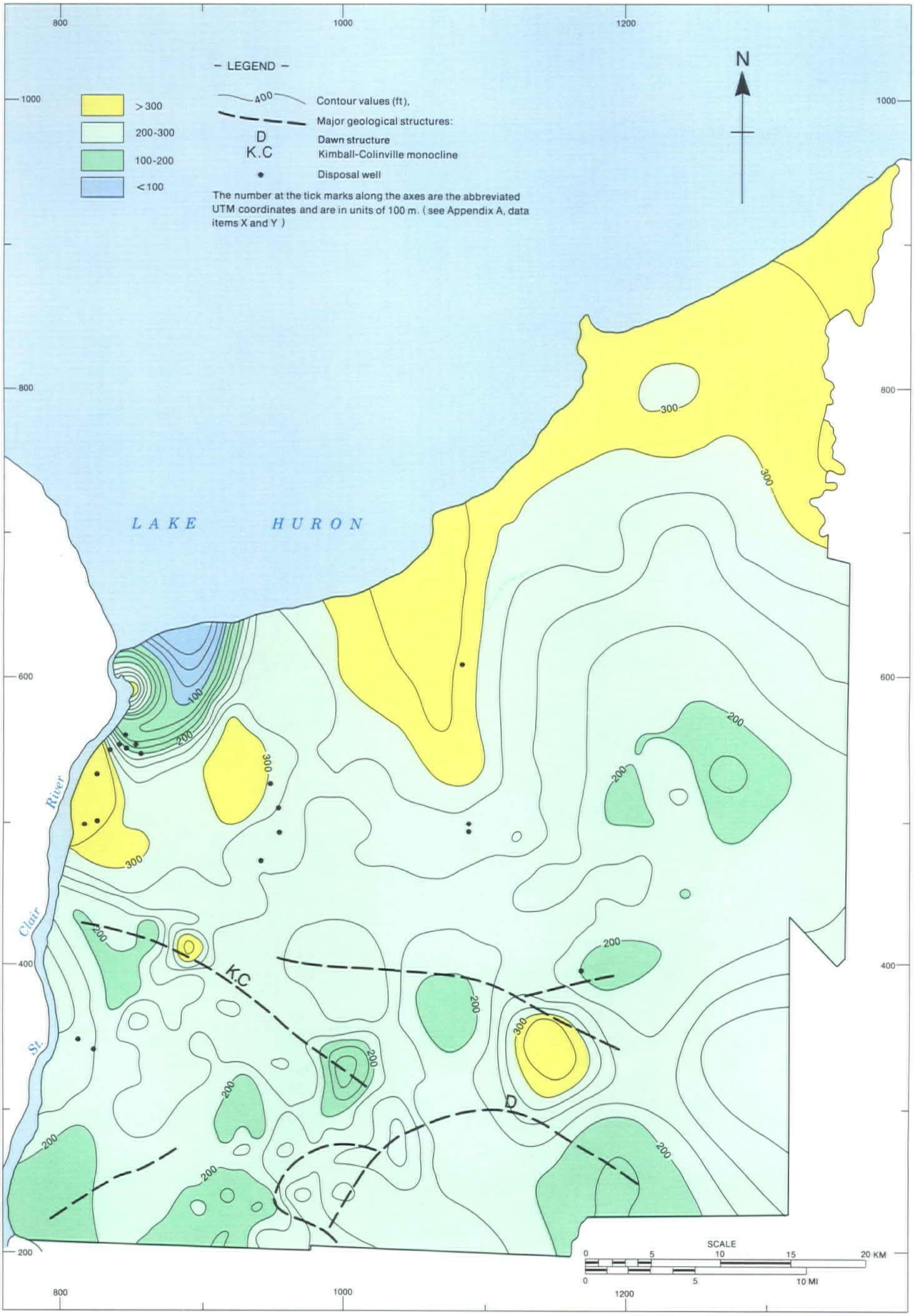

Figure 9. Isopach map of the Lucas Formation.

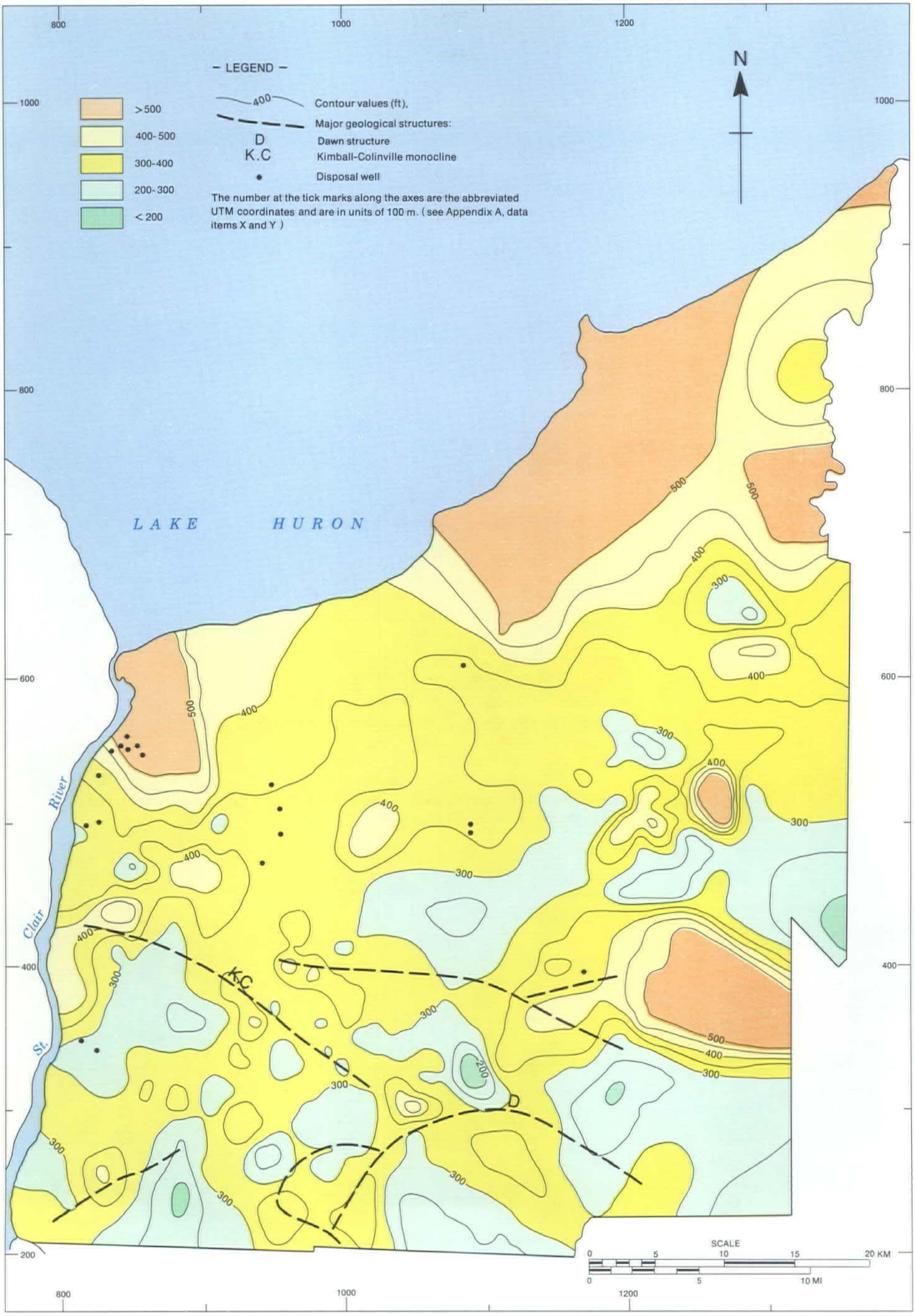

Figure 10. Isopach map of the Detroit River Group.

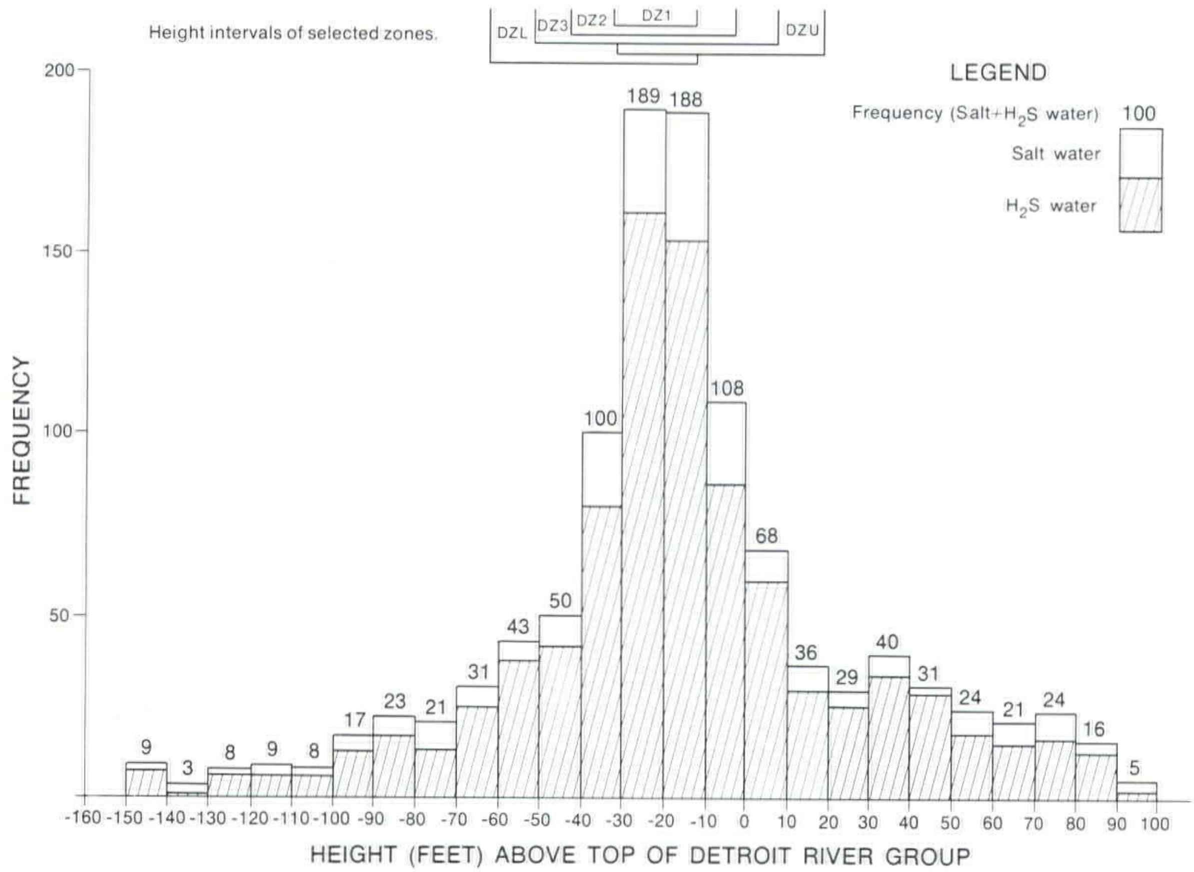

Figure 11. Frequency of available piezometric data for the Dundee Formation and the Detroit River Group vs. the height of the water encounter relative to the top of the Detroit River Group.

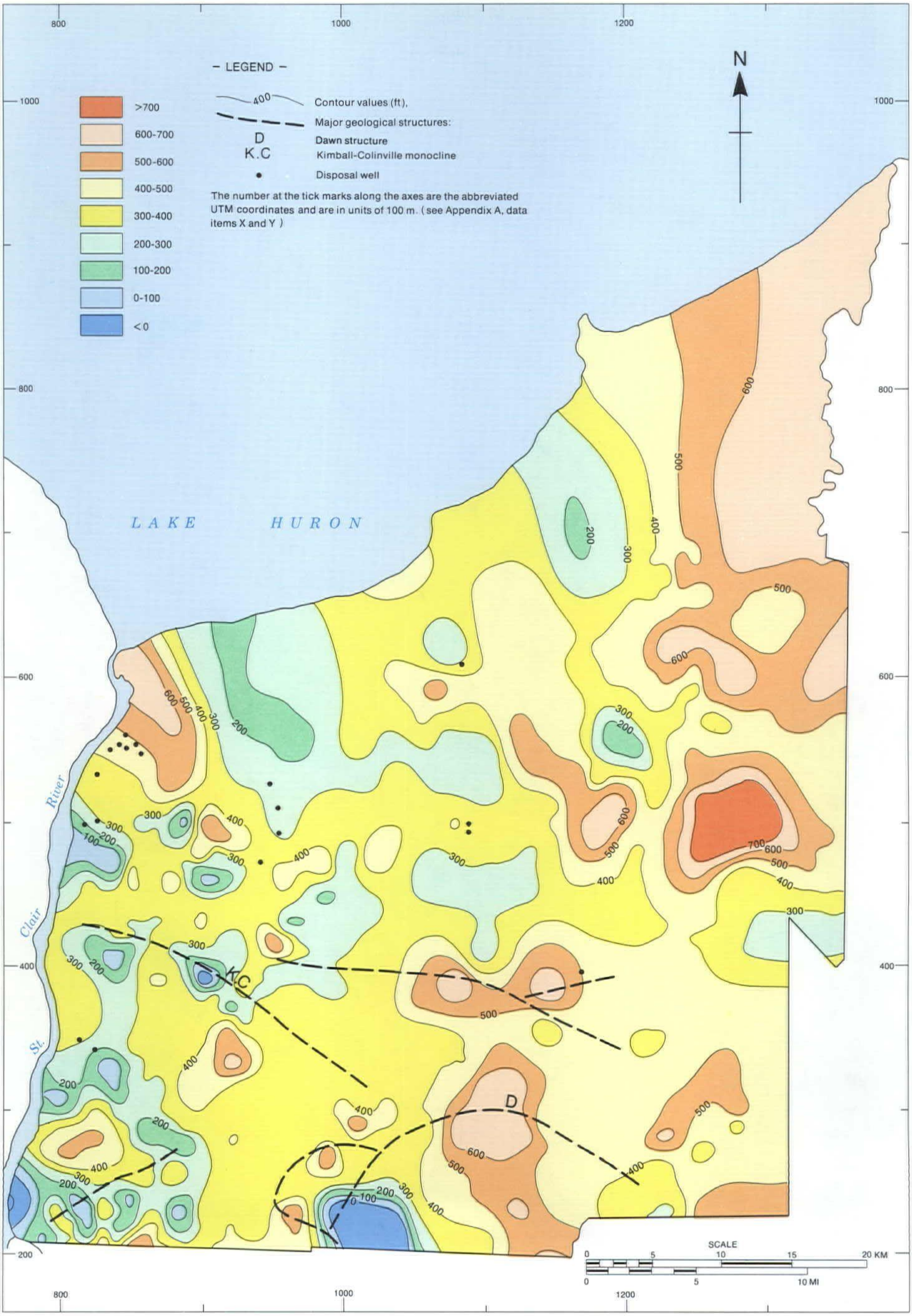

Figure 12. Piezometric map, disposal zone DZ1.

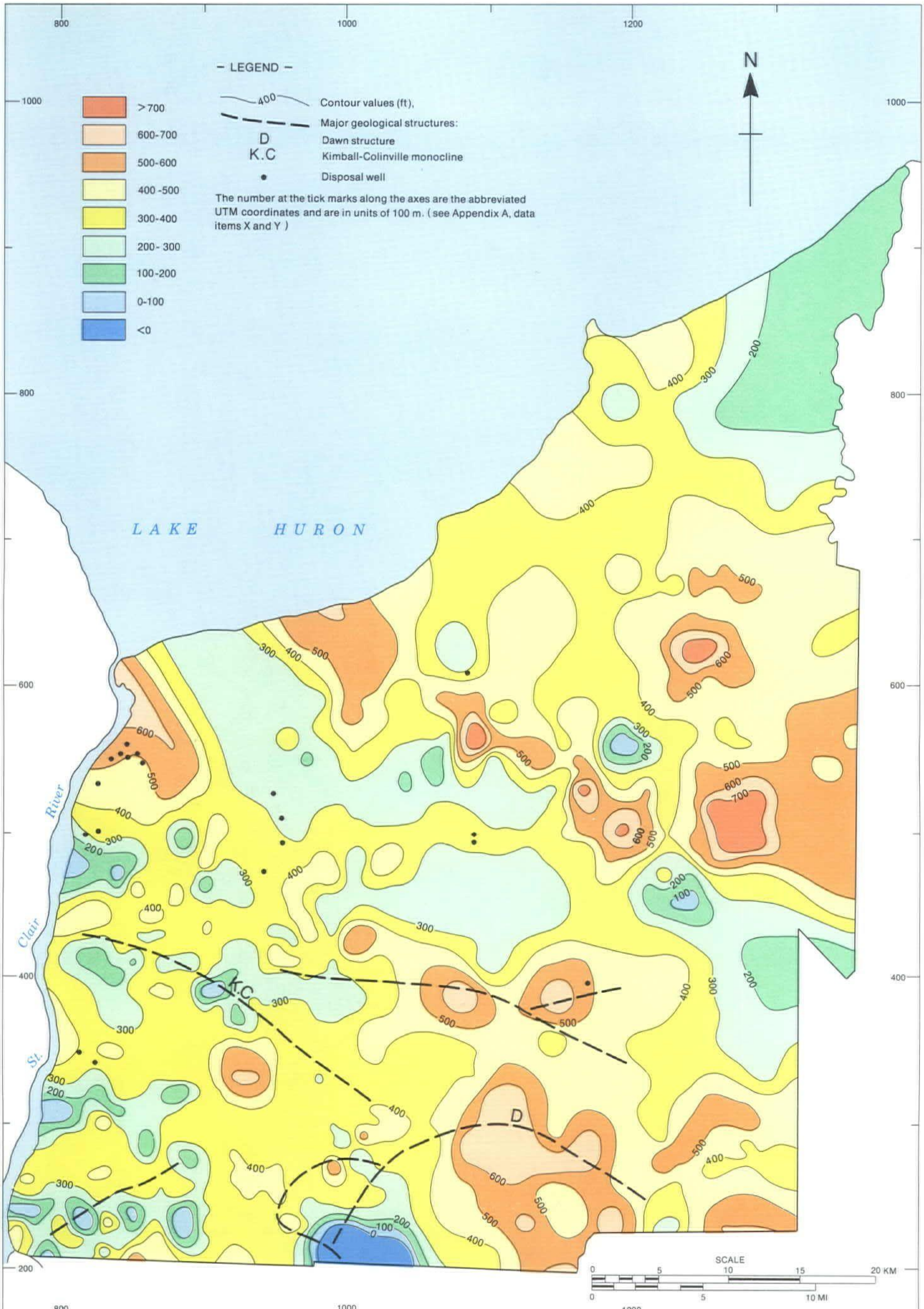

Figure 13. Piezometric map, disposal zone DZ2.

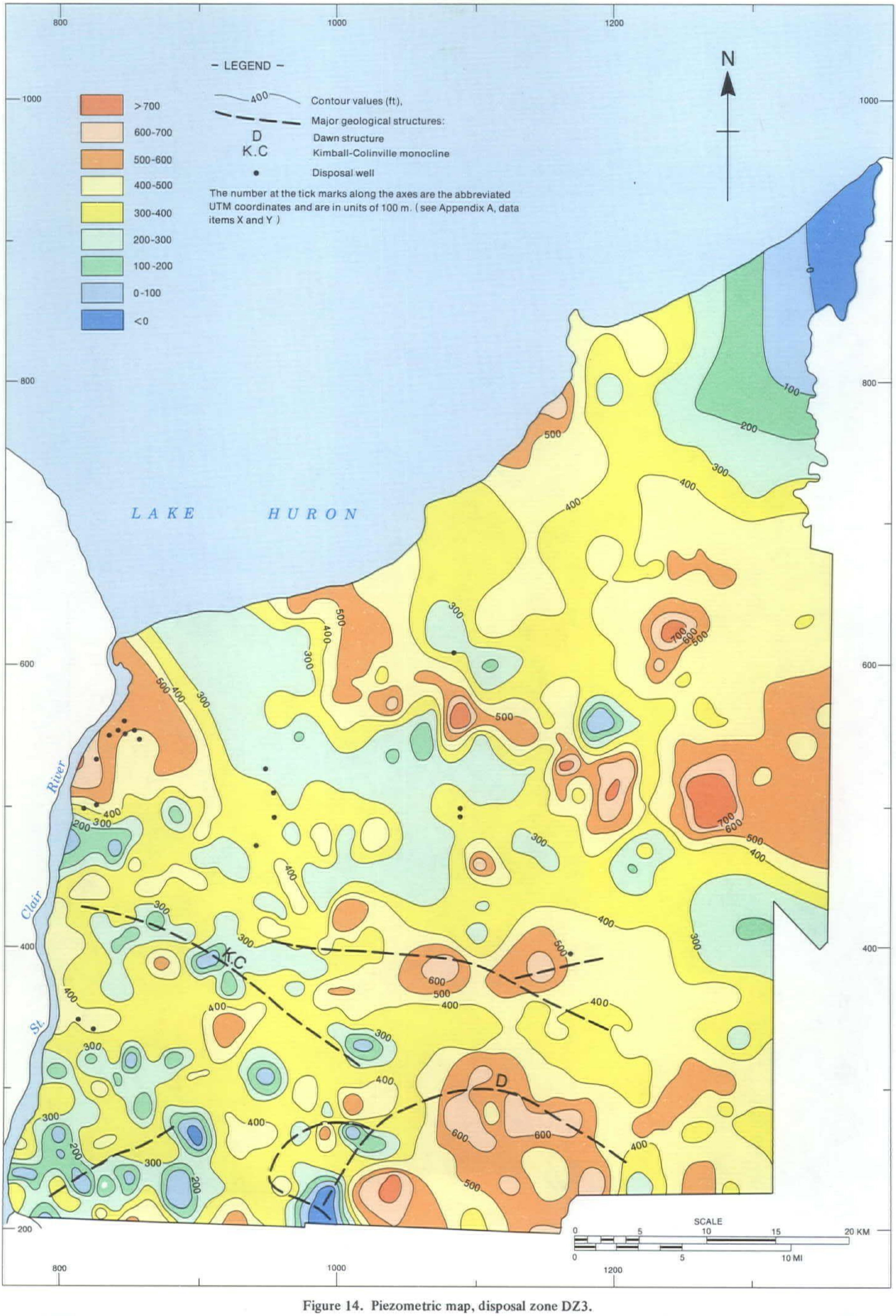

Figure 14. Piezometric map, disposal zone DZ3.

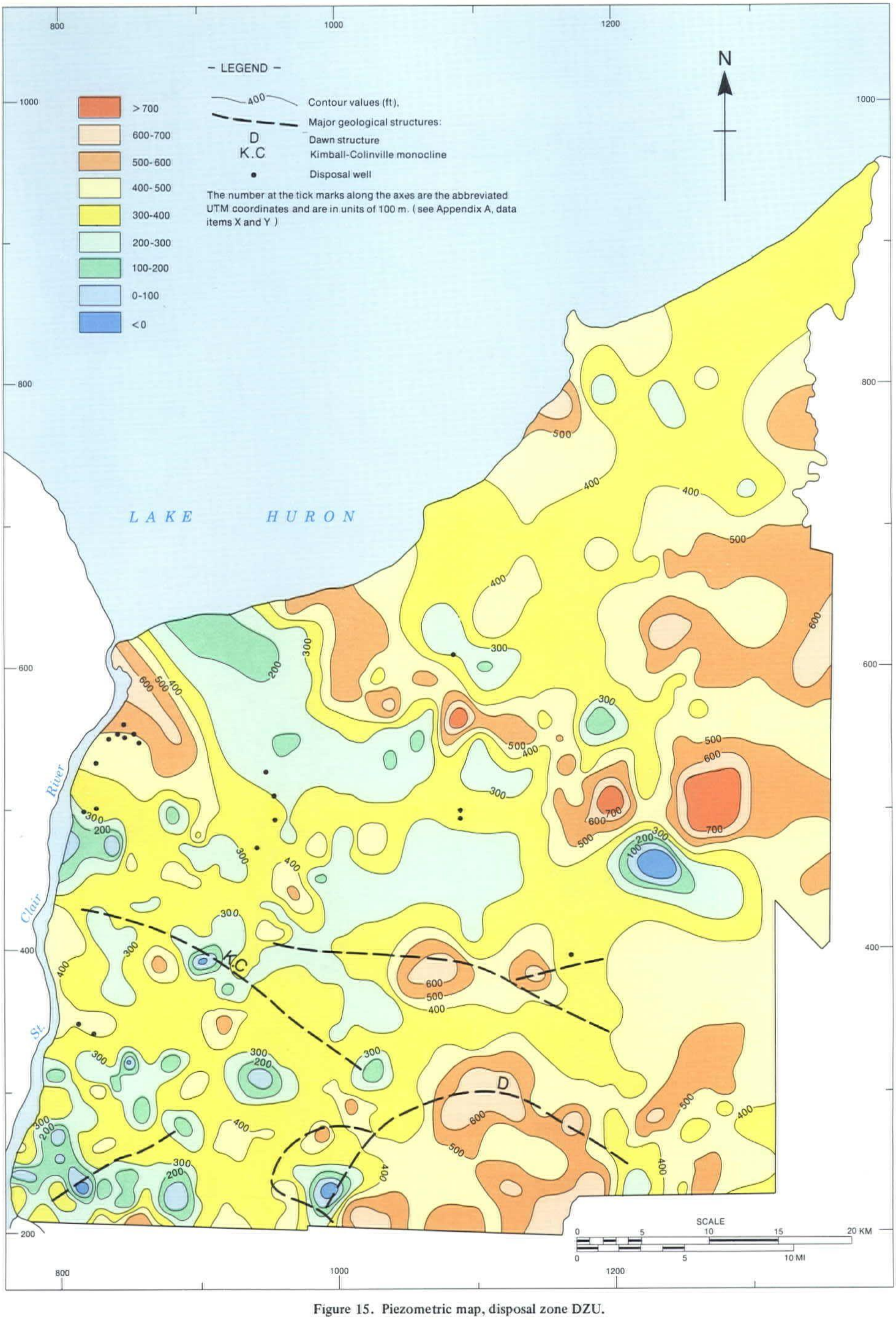

Figure 15. Piezometric map, disposal zone DZU.

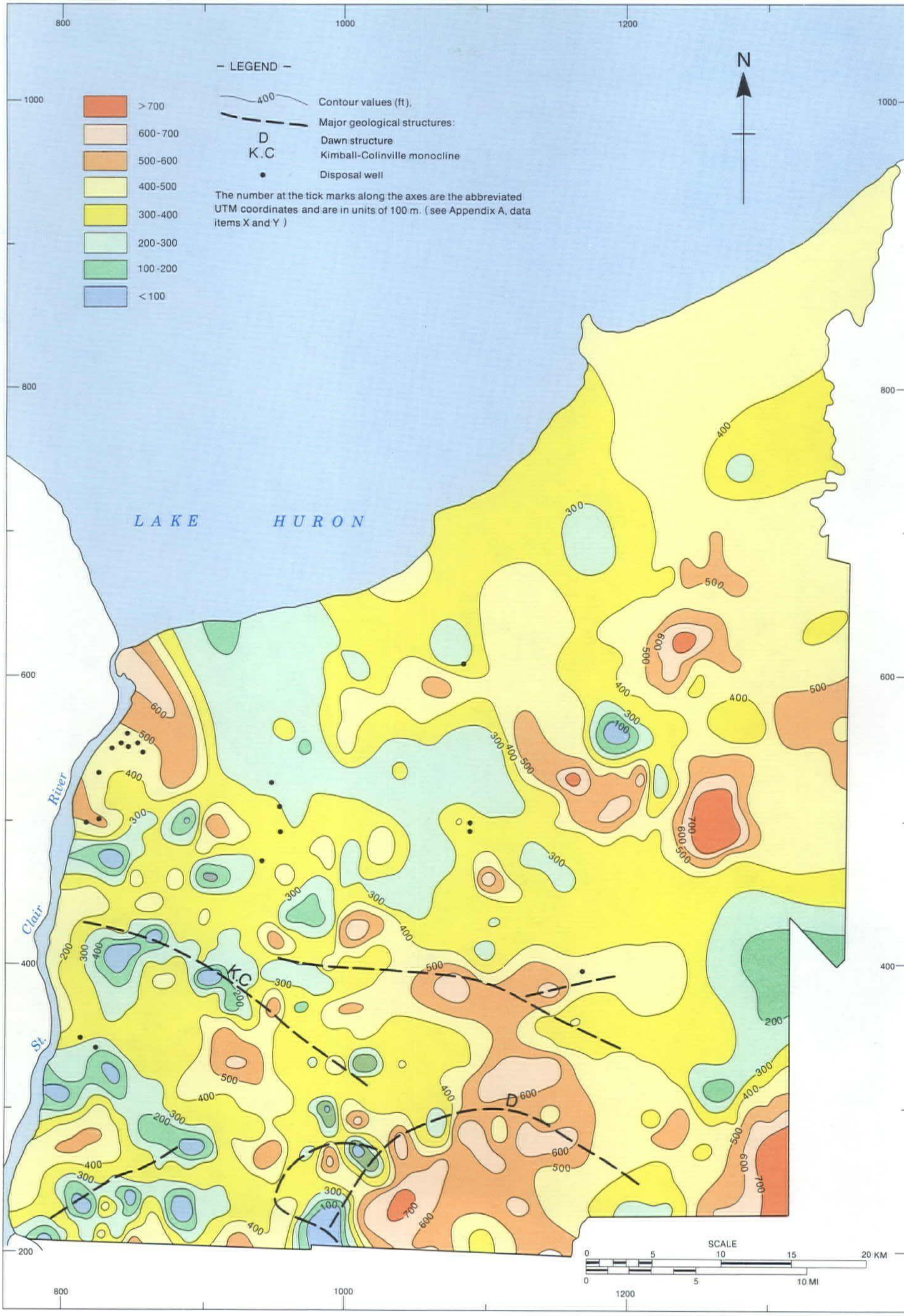

Figure 16. Piezometric map, disposal zone DZL.

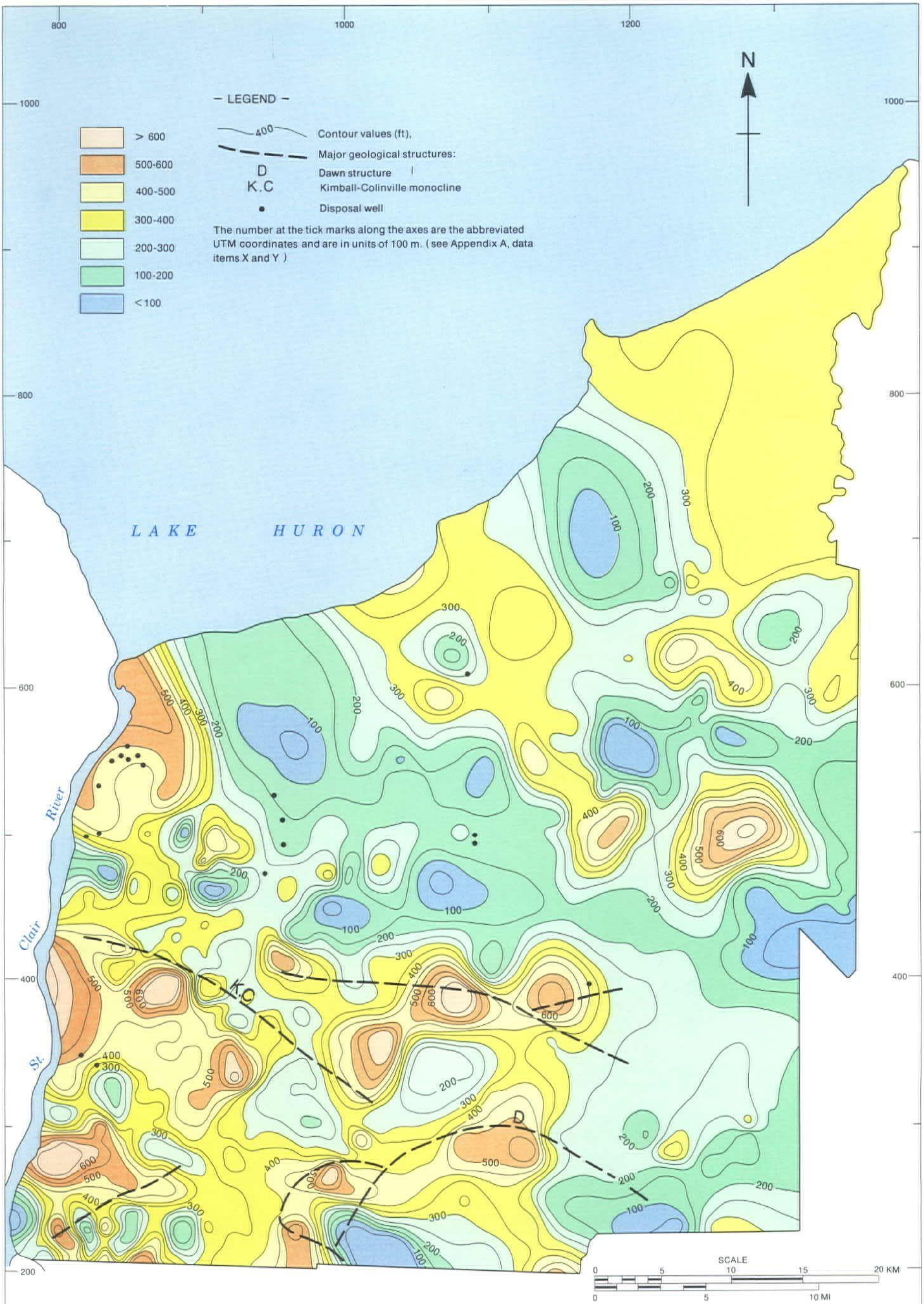

Figure 17. Pressure head, disposal zone DZ1.

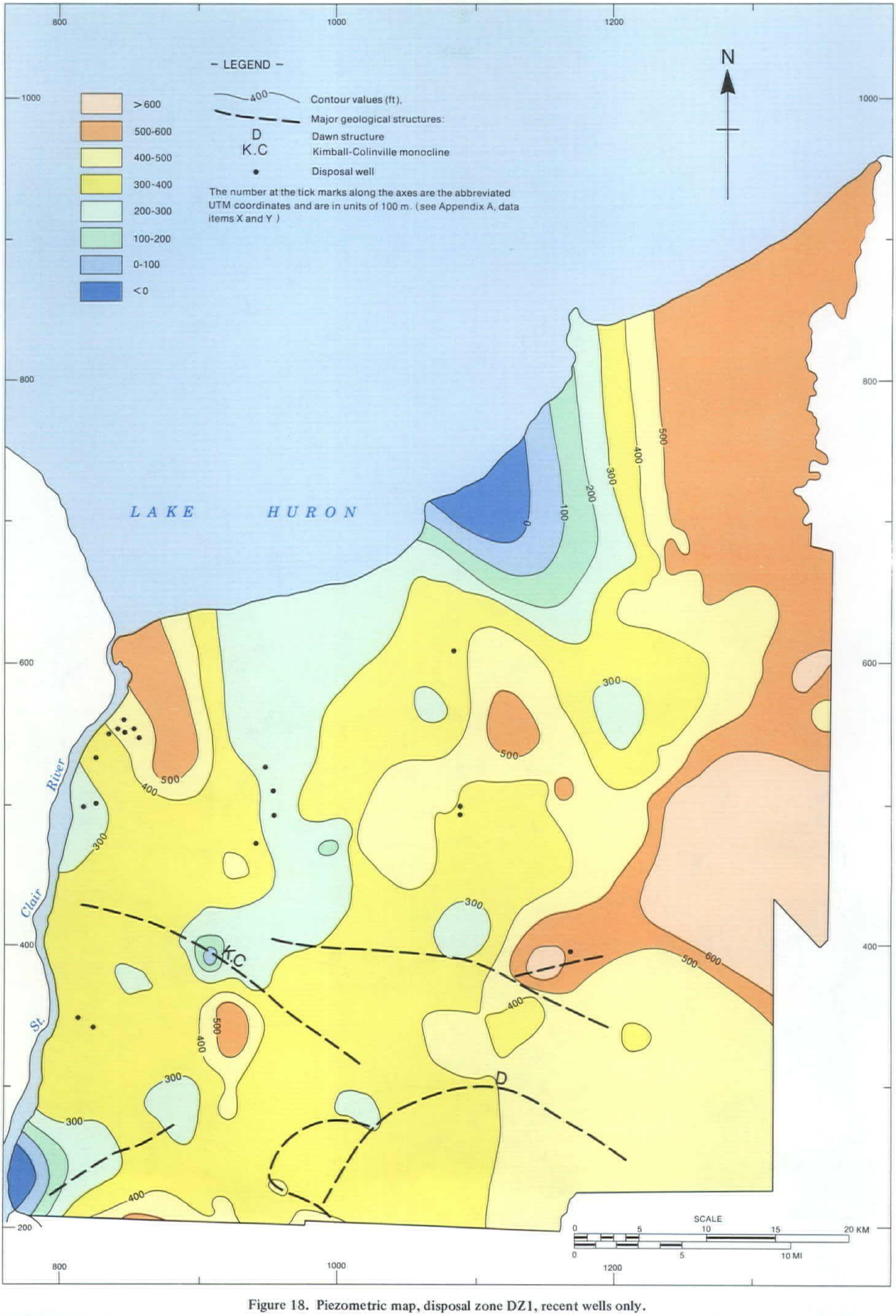

Figure 18. Piezometric map, disposal zone DZ1, recent wells only.

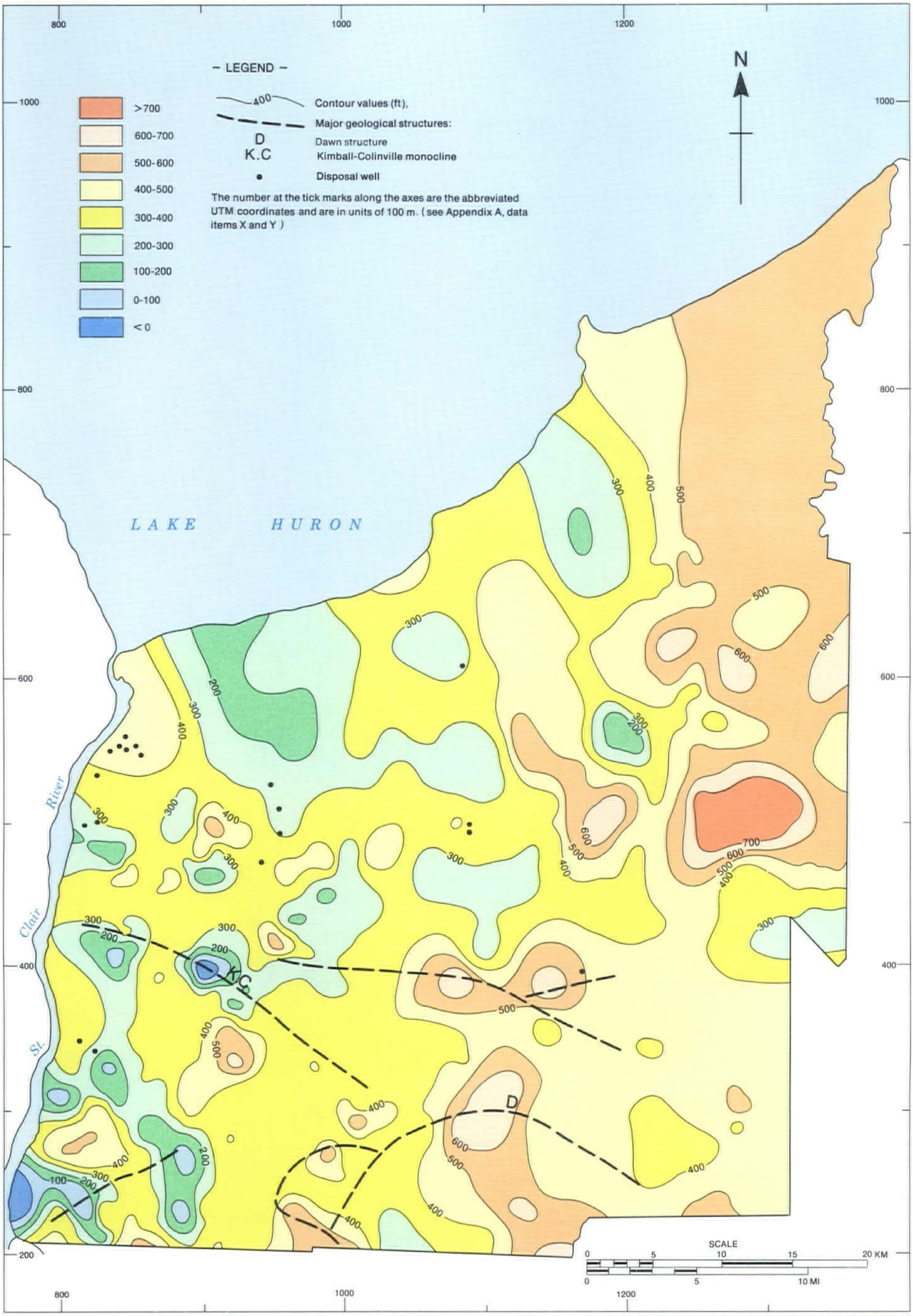

Figure 19. Piezometric map, disposal zone DZ1, sulphurous water only.

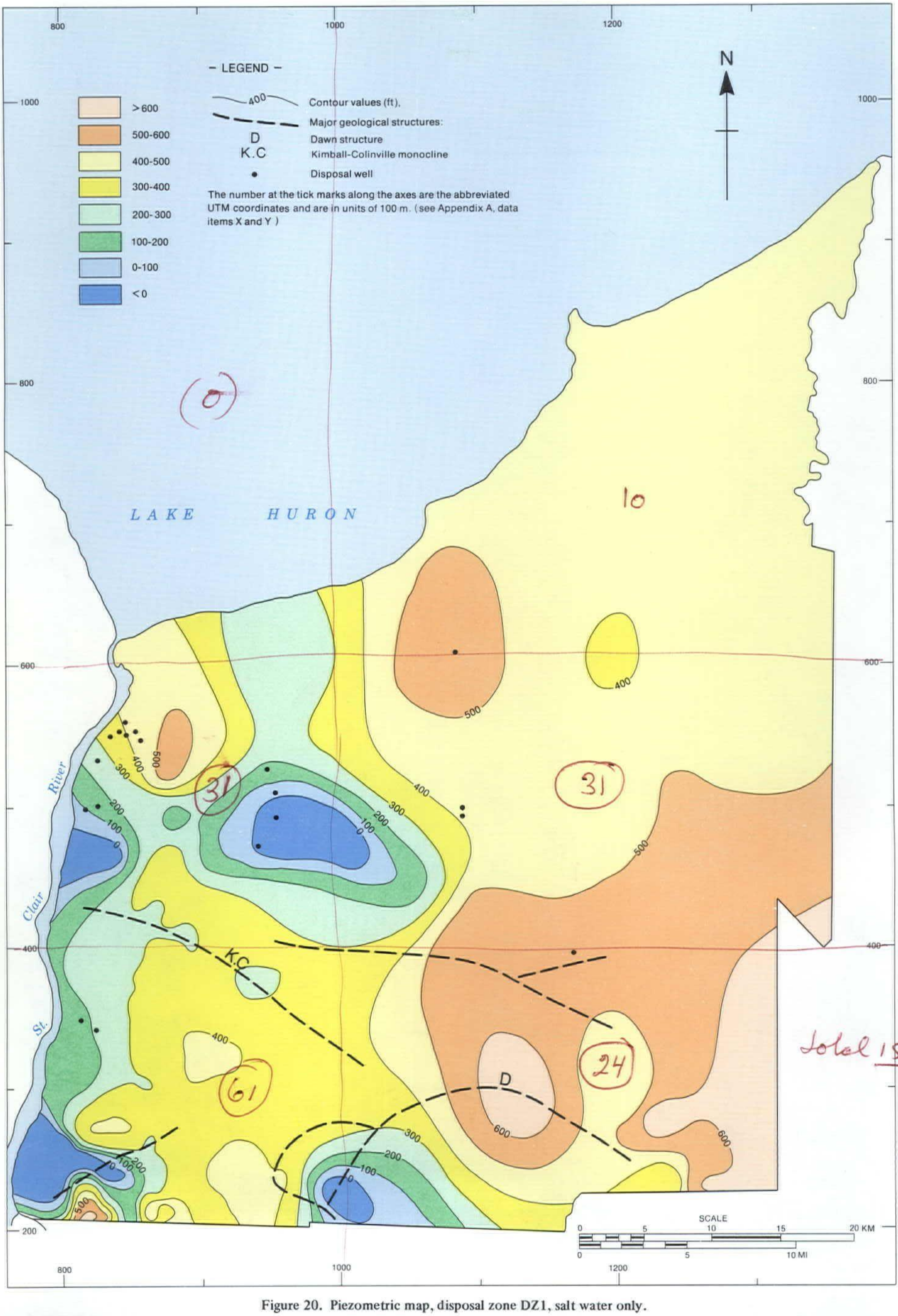

Figure 20. Piezometric map, disposal zone DZ1, salt water only.

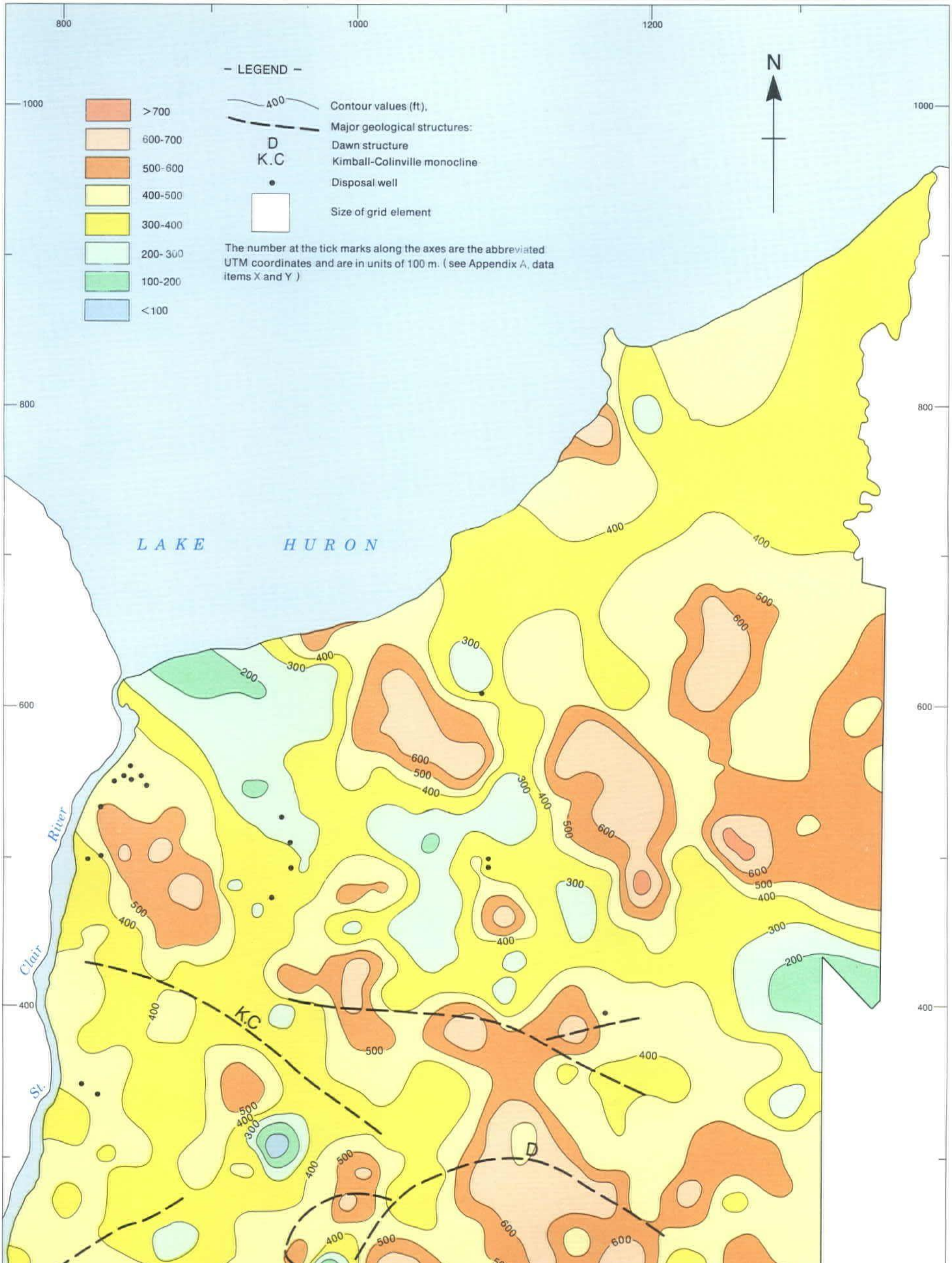

Figure 21. Piezometric map, disposal zone DZ3, maximum values.

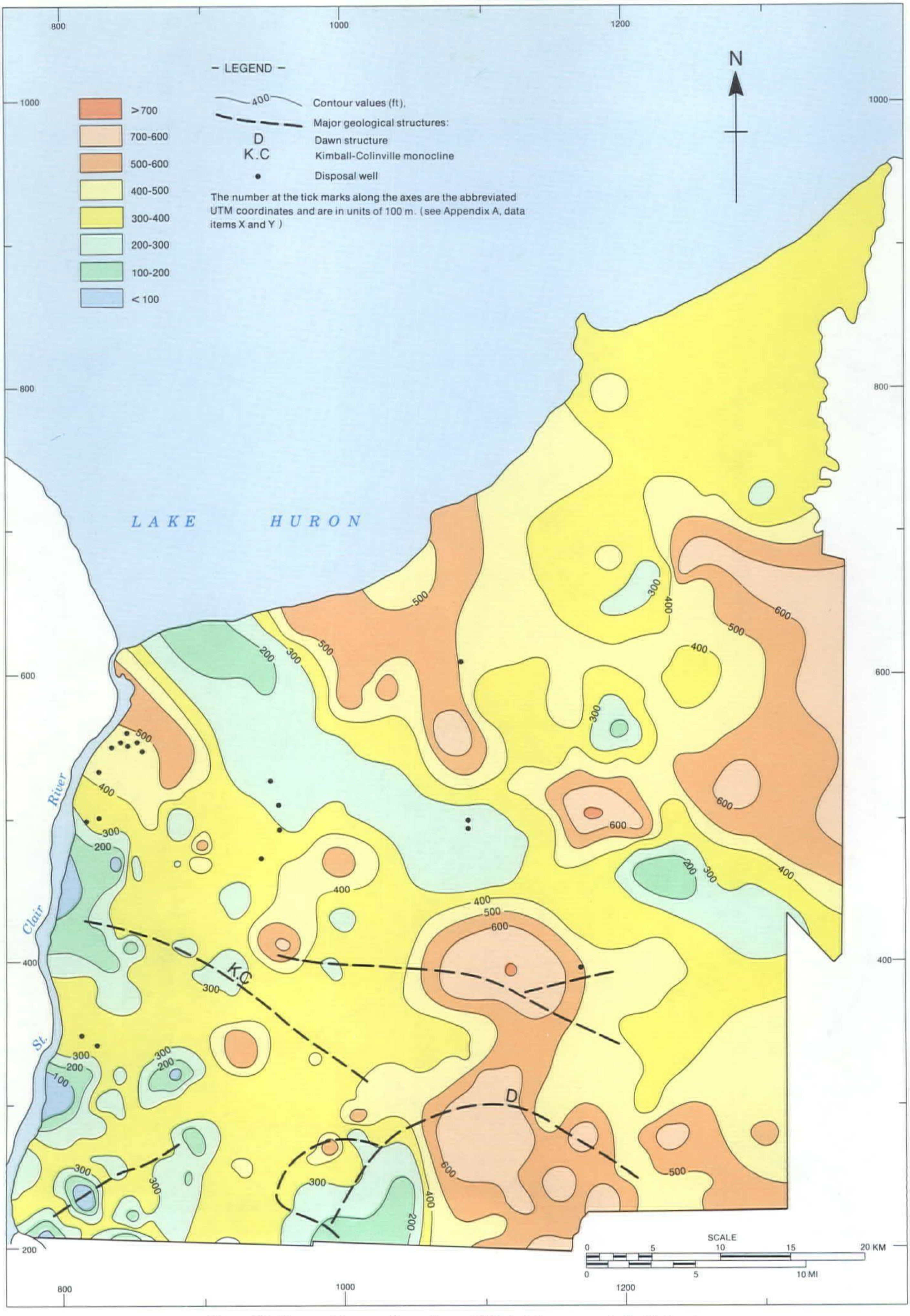

Figure 22. Piezometric map, disposal zone DZ2, data from upper half of interval.

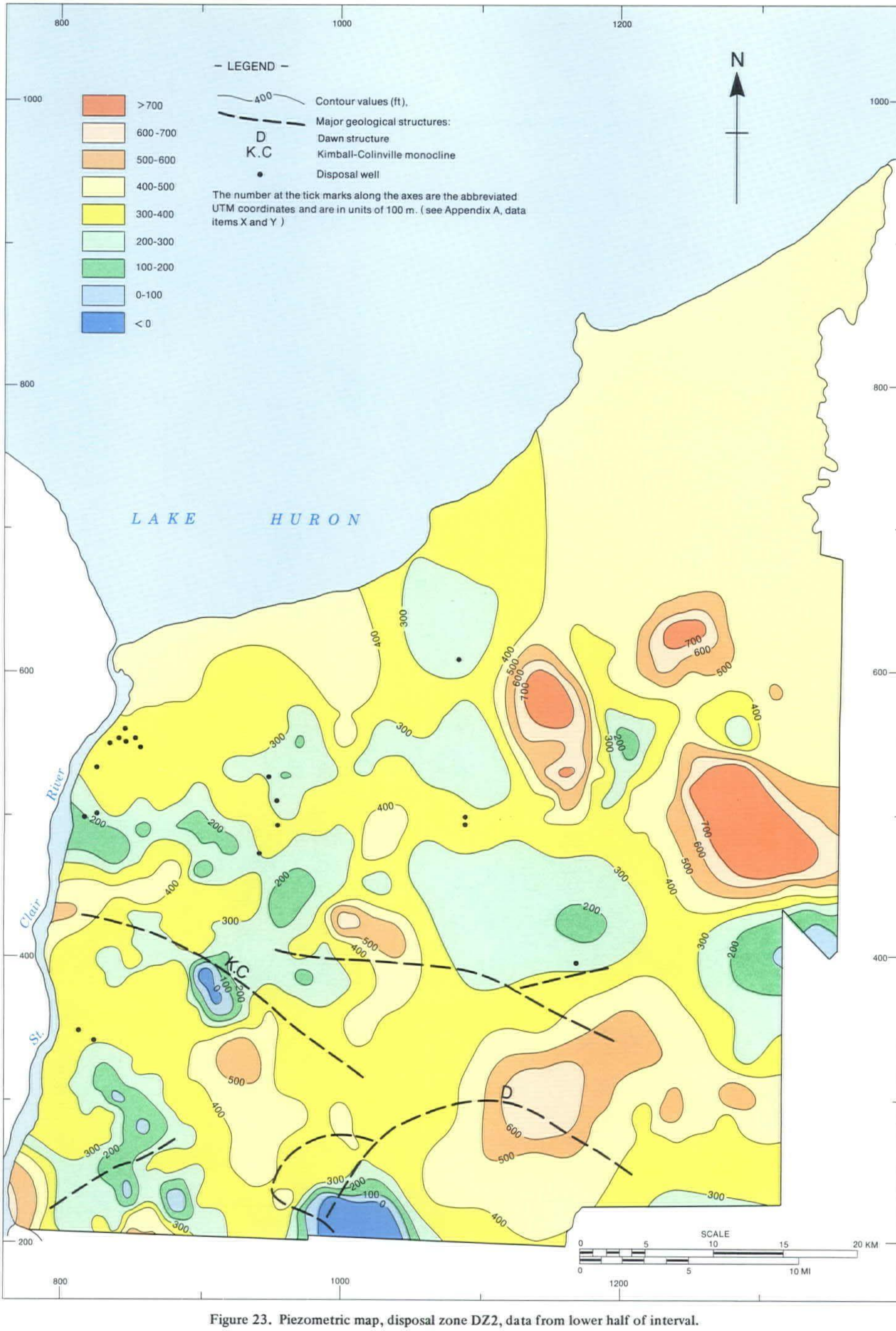

Figure 23. Piezometric map, disposal zone DZ2, data from lower half of interval.

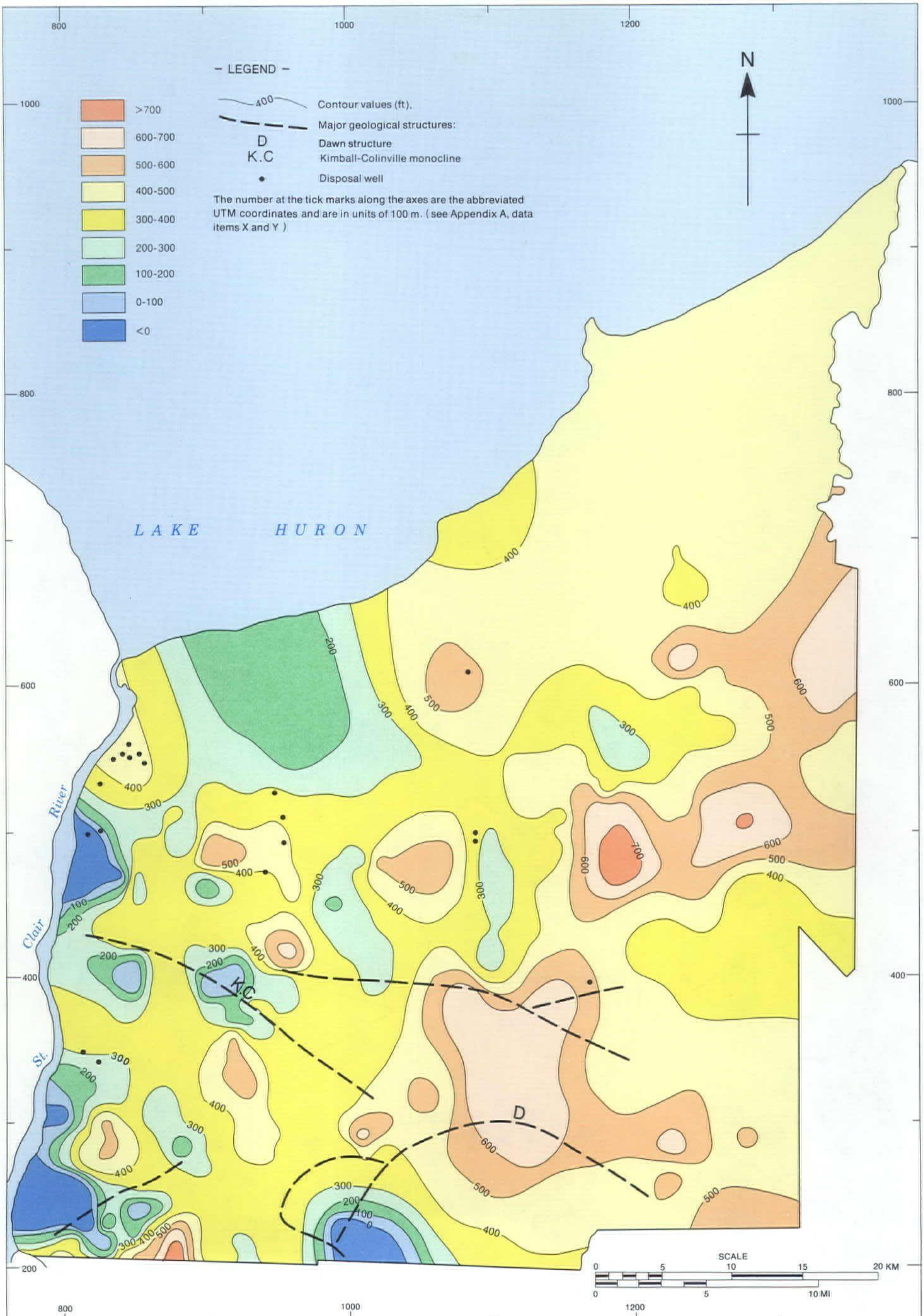

Figure 24. Piezometric map, disposal zone DZ1, random selection of 50 per cent of total data, first group.

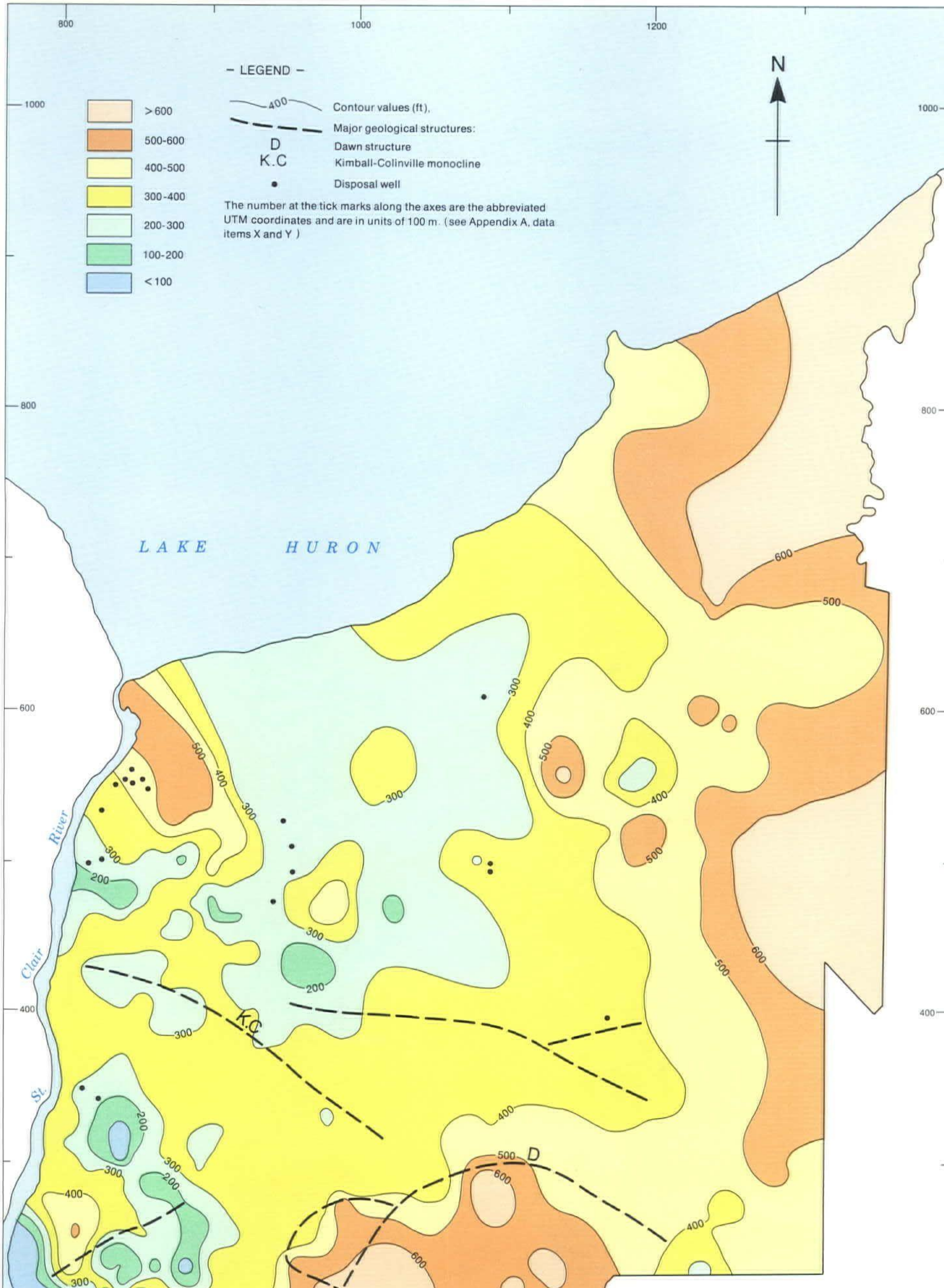

Figure 25. Piezometric map, disposal zone DZ1, random selection of 50 per cent of total data, second group.

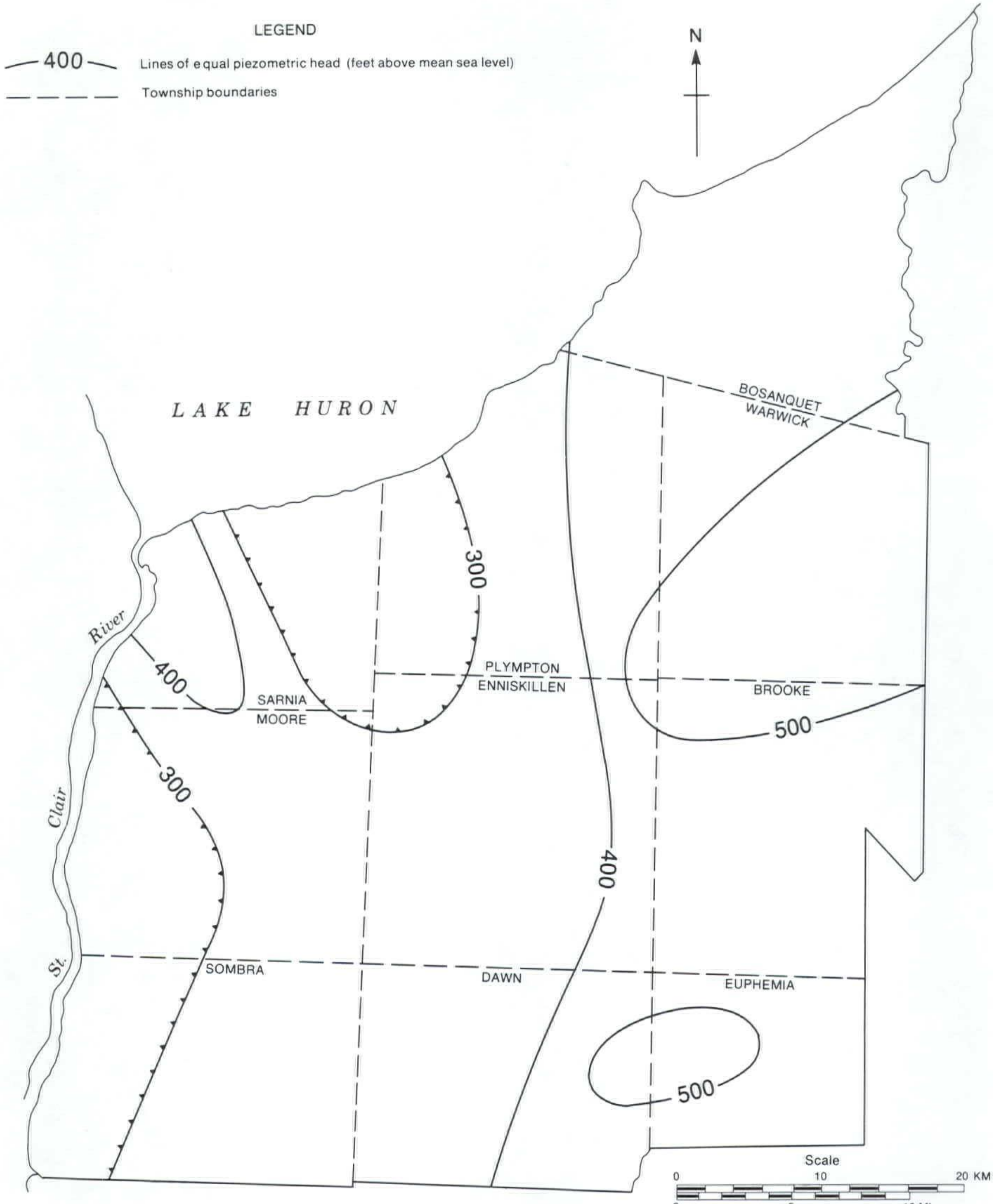

Figure 26. Composite map, showing persistent features only.

Figure 27. Trend surface, least-squares polynomial fit of order 1.

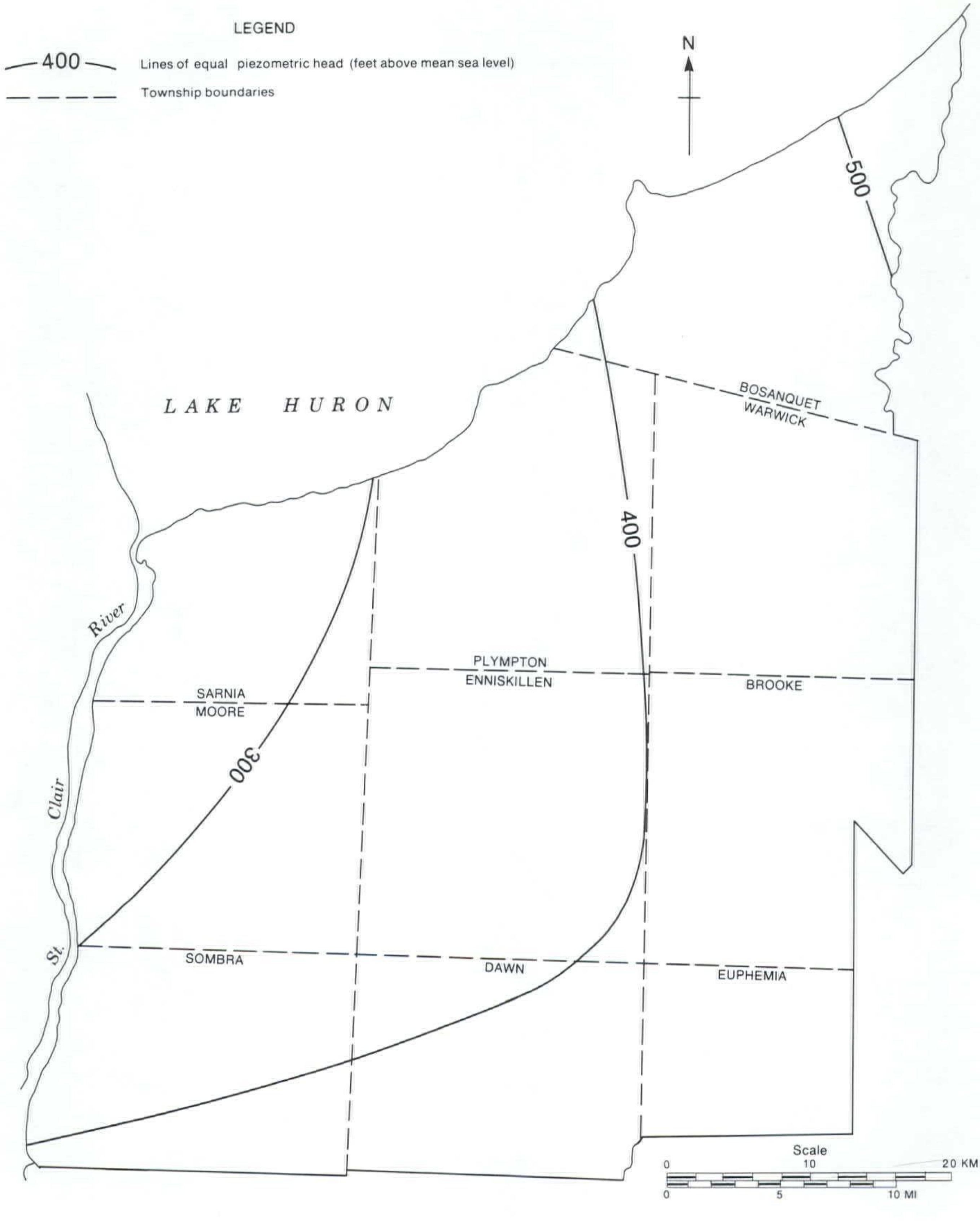

Figure 28. Trend surface, least-squares polynomial fit of order 2.

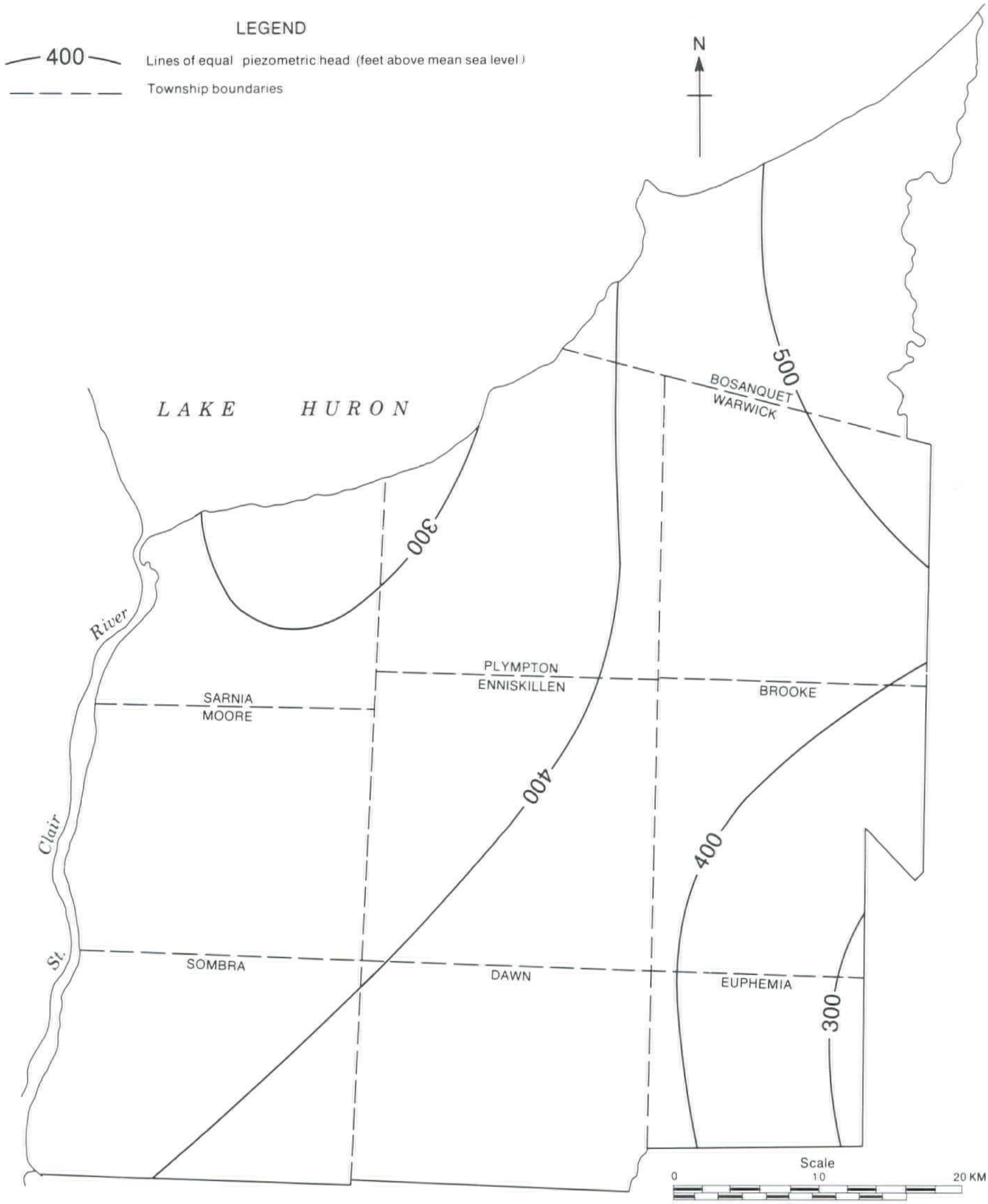

Figure 29. Trend surface, least-squares polynomial fit of order 3.

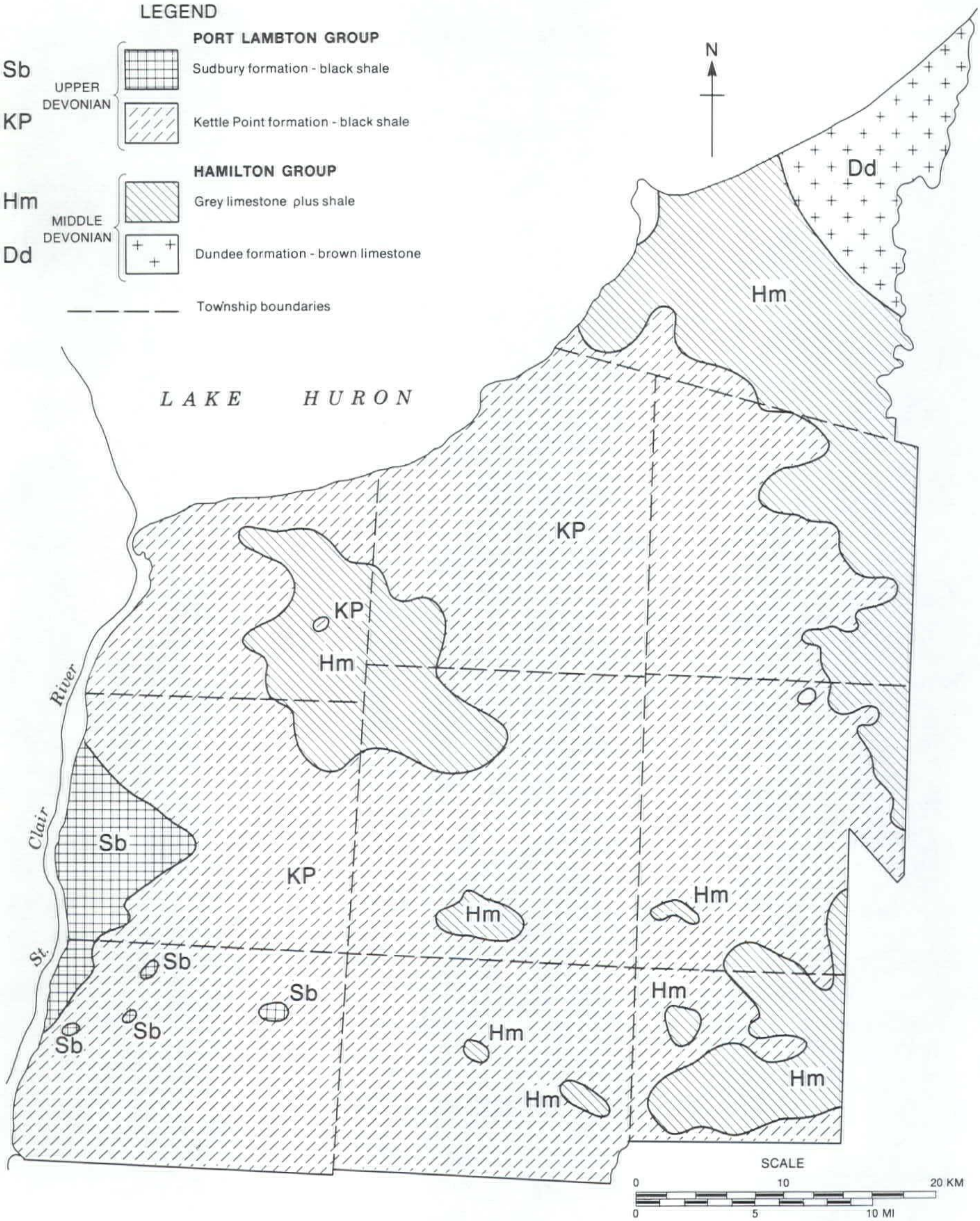

Figure 30. Bedrock geology (after Sanford, 1969).

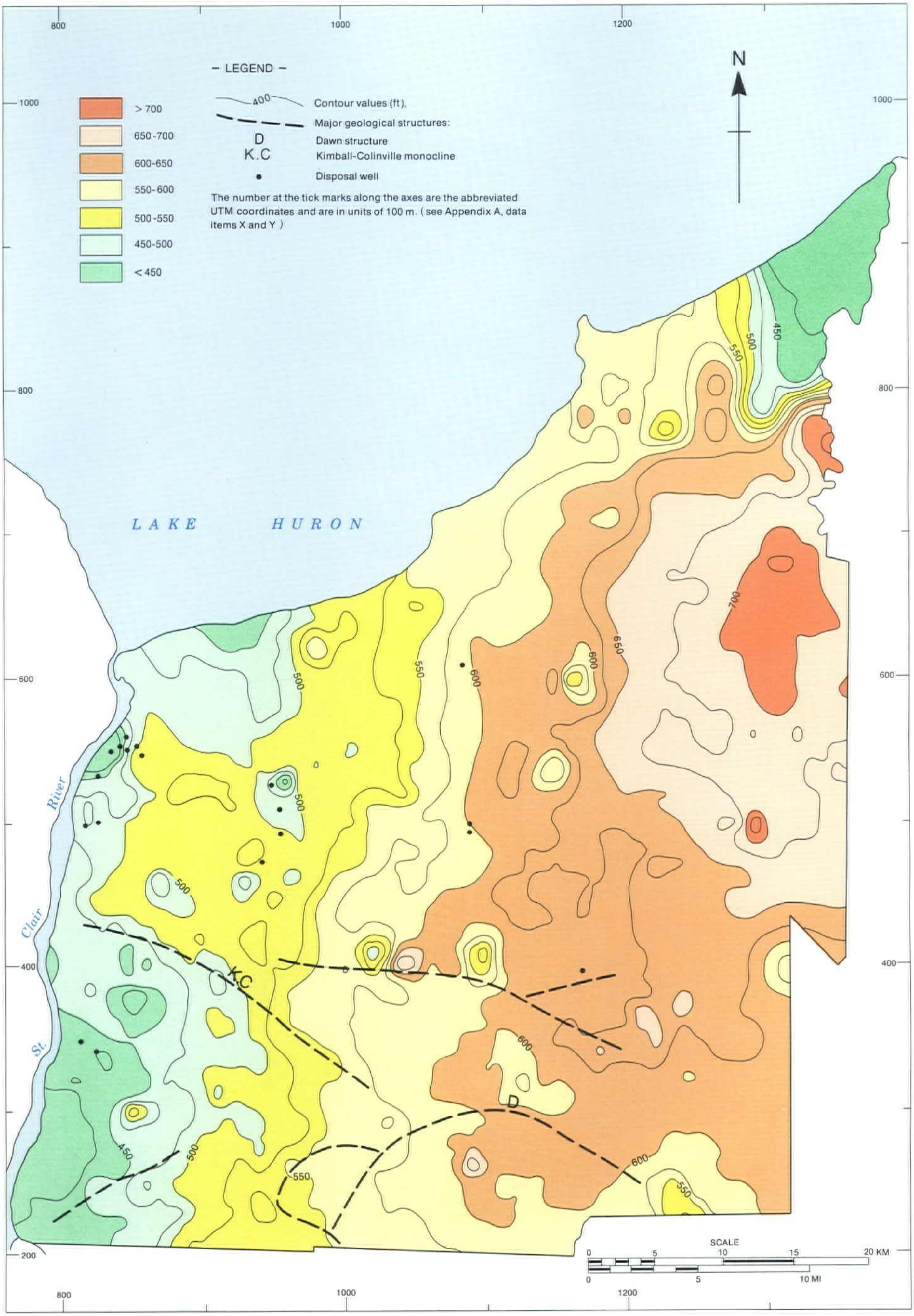

Figure 31. Contour map of the top of the bedrock.

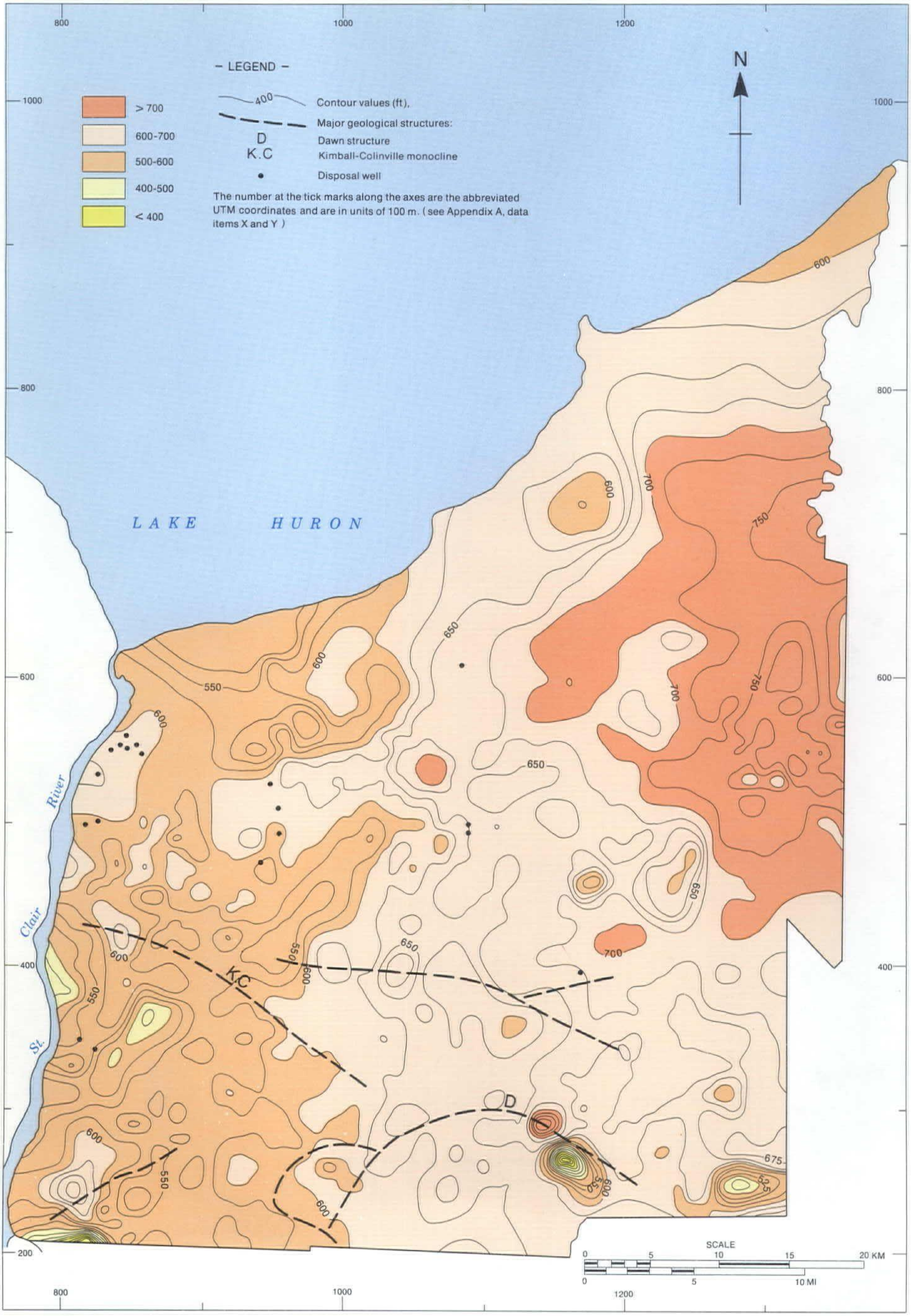

Figure 32. Piezometric head of the fresh-water aquifer.

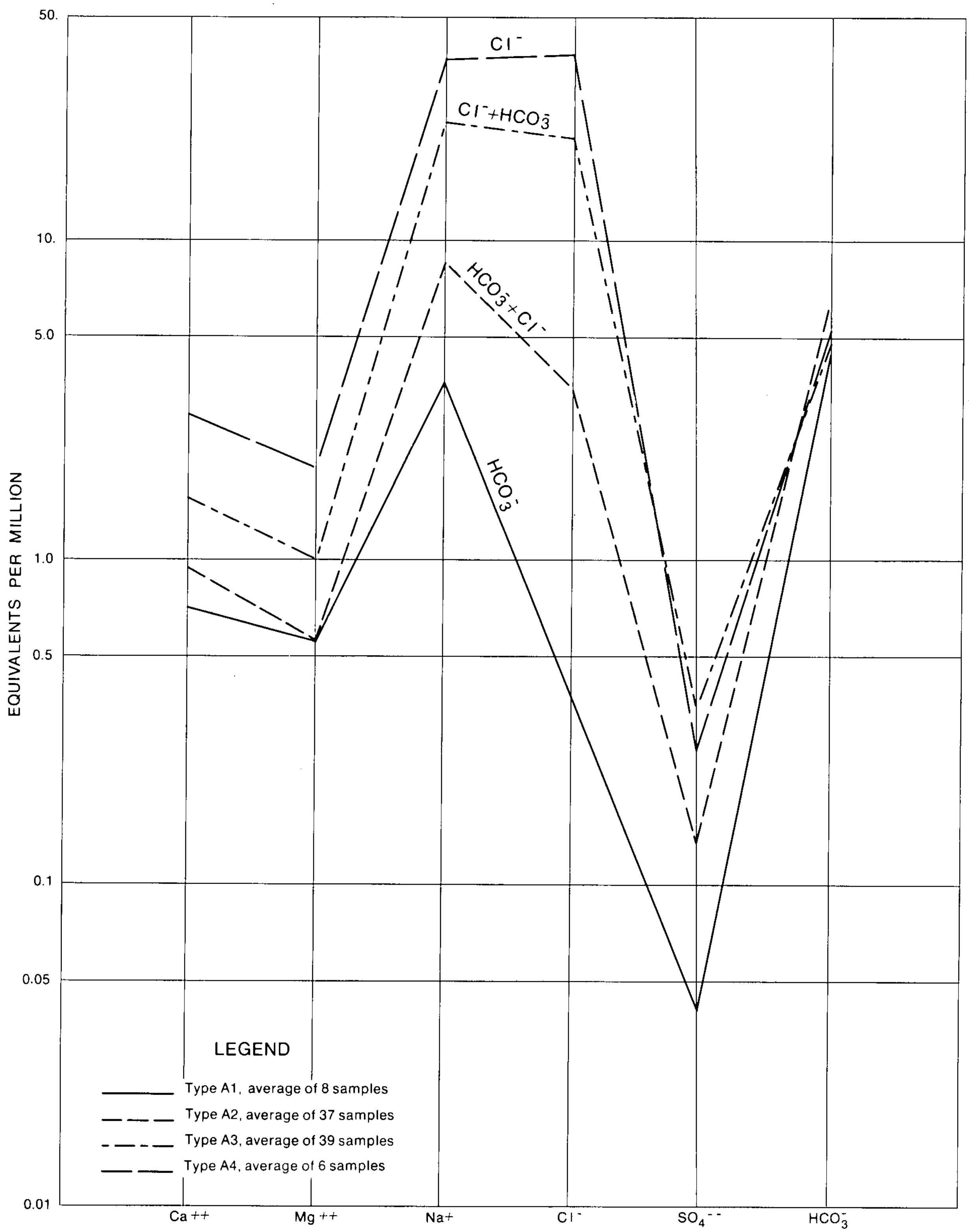

Figure 33. Average composition of chemical types A1 to A4.

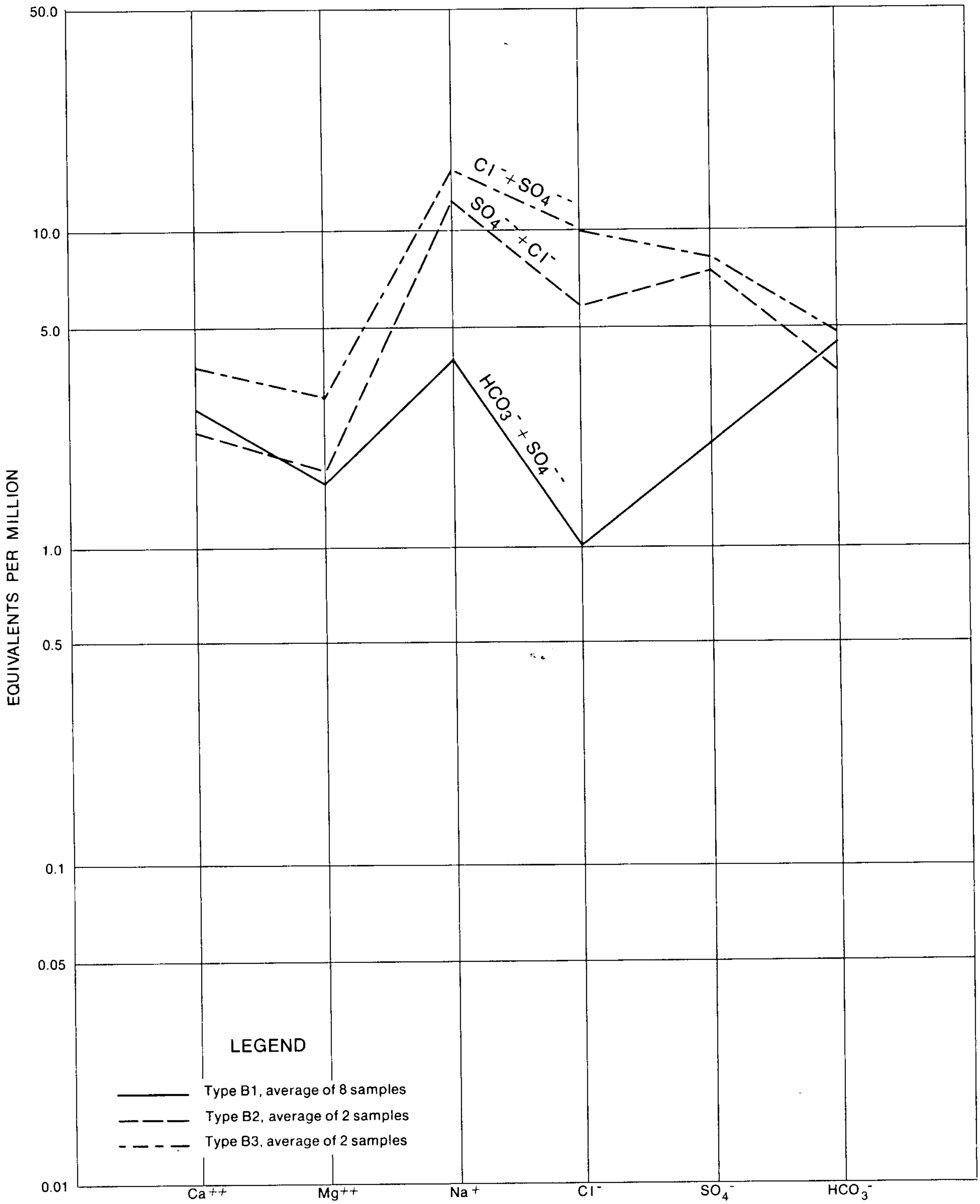

Figure 34. Average composition of chemical types B1 to B3.

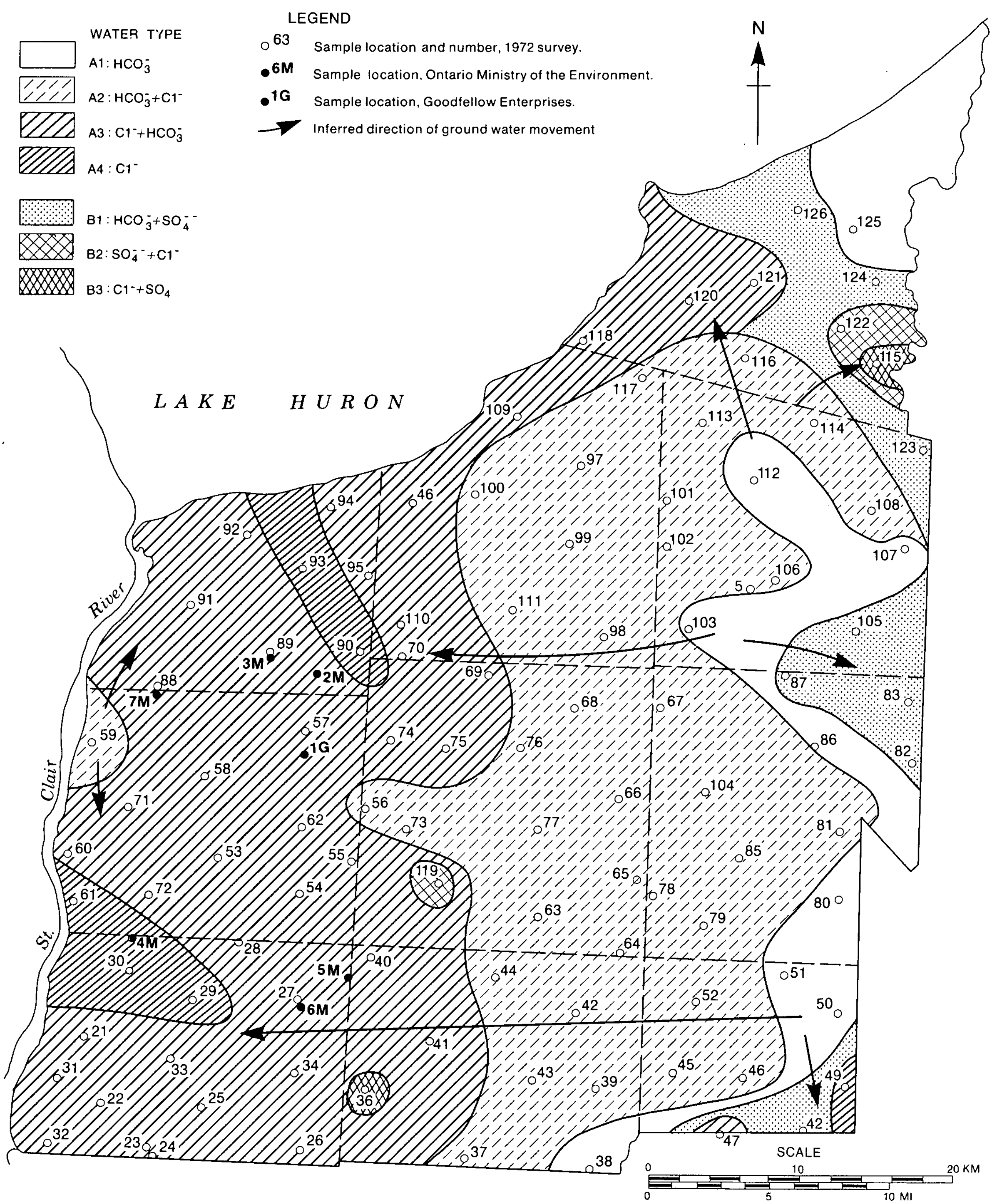

Figure 35. Map of the water chemistry of the fresh-water aquifer and inferred direction of groundwater movement.

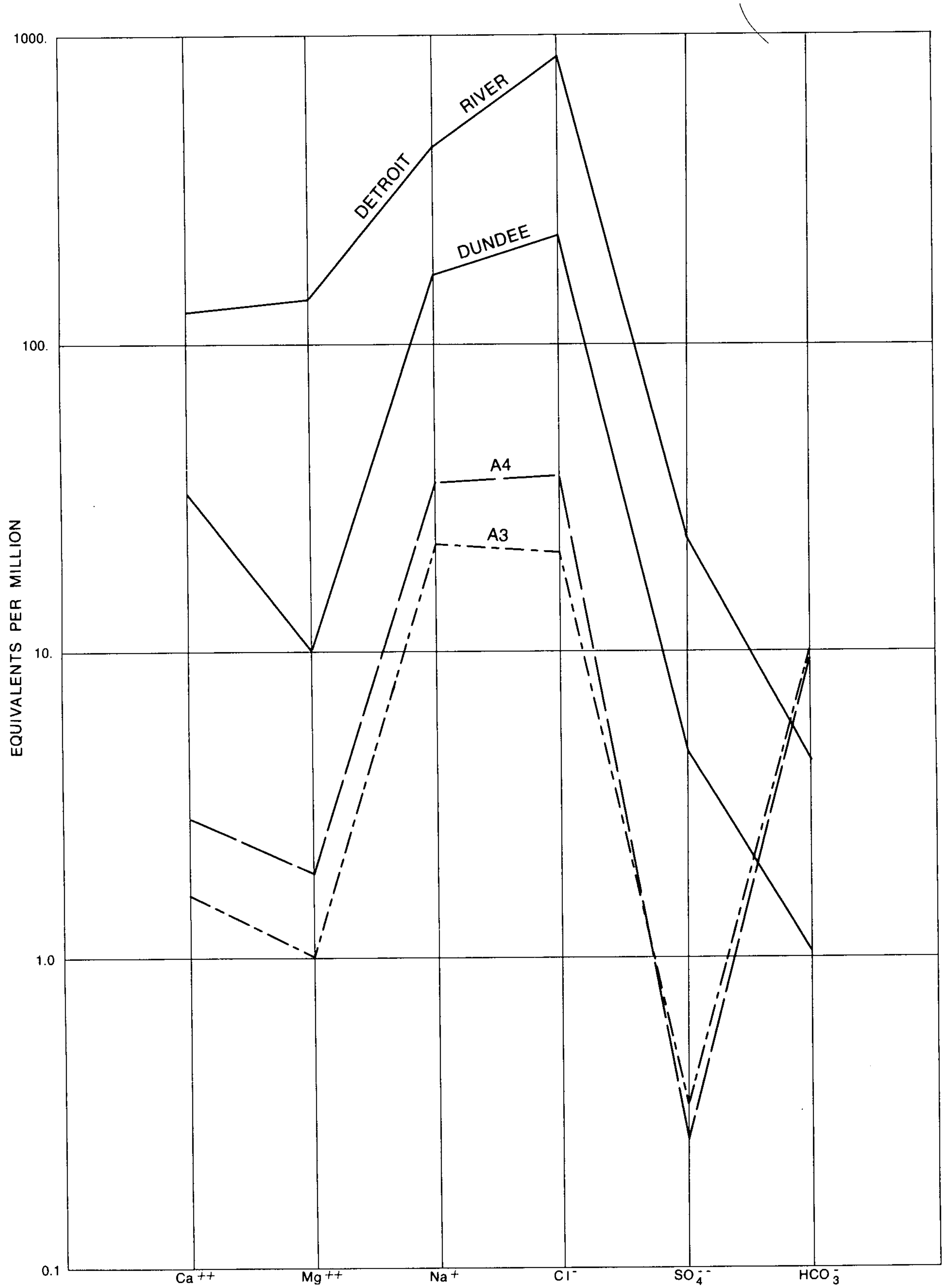

Figure 36. Average chemical compositions of formation waters from the Dundee Formation and the Detroit River Group compared with water types A3 and A4.

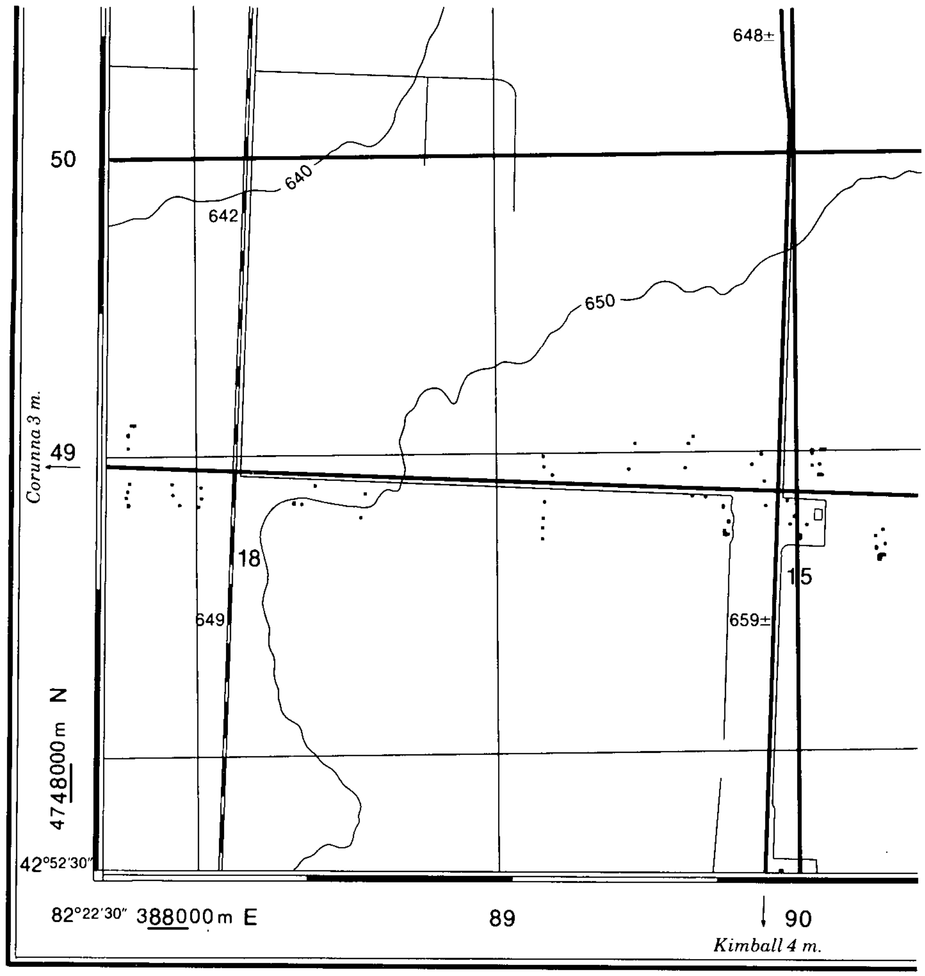

Figure 37. UTM grid coordinates and the x- and y-coordinates coded on the data cards.

Appendix A

Appendix A

DATA ITEMS

Table 2 shows the format of the data cards and the abbreviations for the data items as used in this report and in the various computer programs. A detailed description of the items follows:

WN 4-digit well number assigned to each of the original well records and transferred to each card. Hence, cards for different water encounters in the same well have the same well number. Note that when the well numbers are the same on two or more cards, the location - in fields 2 and 3 - must also be the same, but that the opposite is not necessarily true since two wells may be so closely spaced that they will have the same UTM grid coordinates.

X UTM (Universal Transverse Mercator) grid easting. Figure 37, which is part of National Topographic Series Map 40J/16F, scale 1/25,000, Lucasville, Lambton County, shows the UTM grid and indicates for the most westerly north-south grid line the 3 digits out of the 6-digit UTM grid easting designation that are punched in the X-field; this coding is sufficient to give the location accurate to within 100 m. Since Lambton County lies between UTM eastings 376000 and 440000, these 3 digits uniquely determine all eastings in the county. It has to be kept in mind, however, that those eastings that are coded as a number less than or equal to 400 are farther east than those coded greater than or equal to 760. In the preparation of card decks for input to the contouring program the proper relative easting was obtained by adding one thousand to all eastings less than or equal to 400.

Y UTM grid northing. The 3 digits of the 7-digit UTM designation that were coded are shown in Figure 37 for the most southerly east-west grid line. They are sufficient to determine locations accurate to within 100 m. Since Lambton County lies between UTM northings 4718000 and 4796000, the code correctly indicates the relative northings in the County.

WQ Type of quality of the water as shown on the original record; only 5 distinct codes appear, right justified, in this field:

SALT	-	salt water
H2S	-	sulphurous salt
FR	-	fresh water
NIND	-	water type was not indicated on the record
blanks	-	used only where WQ is not applicable, i.e. on cards containing only geologic information.

In this report, references to any of these five chemical water types will always be included in round brackets, e.g. (H2S) to distinguish them from other groups of abbreviations.

EWE Elevation at which the water was encountered (feet above mean sea level).

SWE Piezometric elevation, i.e. elevation to which the water level recovered (feet above mean sea level).

FN The name of the formation. Table 3 shows the nomenclature for the palaeozoic strata as proposed by Beards (1967) and revised by Brigham (1971). The abbreviations entered—right justified—in the FN field are shown in the square brackets to the right of the unit name. In this report formation-name abbreviations will always be enclosed in square brackets to distinguish them from other groups of abbreviations.

The coding for the Detroit River Group needs some additional explanation. Whenever on the original record the Group was subdivided into the Lucas and Amherstburg Formations the *formation* name,[L] or [A], was recorded on the card; if the group was not subdivided on the original record, one of the abbreviations, [DR], [DRB], or [DRC] was used. [DR] was used only when the next lower formation picked was the Bois Blanc; [DRB] was used if the top of the Bois

Table 2. Data Card Format.

Card columns	1–4	6–8	10–12	14–17	19–23	25–29	31–34	36–40	42–46	48–52	54–58
Numeric or Alphabetic	3 3 3 3	3 3 3	3 3 3	A A A A	3 3 3 3 3	3 3 3 3 3	A A A A	3 3 3 3 3	3 3 3 3 3	3 3 3 3 3	3 3 3 3 3
Field No.	1	2	3	4	5	6	7	8	9	10	11
Description	WELL NO.	UTM EASTG.	UTM NORTHG.	WATER TYPE	ELEV. OF WATER BEARING ZONE	ELEV. OF STATIC WATER LEVEL	FORMATION NAME	ELEV. OF TOP OF FORMATION WHERE WATER ENCOUNTERED	DEPTH OF WATER ZONE BELOW TOP OF FORMATION*	THICKNESS OF FORMATION	YEAR WELL WAS DRILLED
Field Name	WN	X	Y	WQ	EWE	SWE	FN	ETF	DTF	FT	YR

*In some of the decks DTF is replaced by HWE = the elevation of the water-bearing zone relative to the top of the Detroit River Group

I4, 2(1X,I3), 1X,A4, 2(1X,I5), 1X,A4, 4(1X,I5)

Table 3. Paleozoic Stratigraphic Column for Southwestern Ontario (after McLean, 1968) and Computer Card Codes.

GENERALIZED GEOLOGICAL SECTION SOUTHWESTERN ONTARIO

PERIOD	ERA	GROUP OR FORMATION	SECTION	LITHOLOGY	CODE	POTENTIAL DISPOSAL HORIZON
		DRIFT		CLAYS, GRAVELS		
DEVONIAN	UPPER	PORT LAMBTON		SANDSTONE, SHALE	(PL)	
DEVONIAN	UPPER	KETTLE POINT		SHALE	(KP)	
DEVONIAN	MIDDLE	HAMILTON		LIMESTONE, SHALY LIMESTONE	(H)	
DEVONIAN	MIDDLE	DUNDEE		LIMESTONE	(D)	
DEVONIAN	MIDDLE	DETROIT RIVER (LUCAS, AMHERSTBURG)		DOLOMITE, CHERTY LIMESTONE	(DR)* (L) (A)	Potential in Lambton County and parts of Kent and Elgin Counties.
DEVONIAN	LOWER	BOIS BLANC		CHERTY LIMESTONE	(BB)	Local possibilities in parts of Elgin and Norfolk Counties.
SILURIAN	UPPER	BASS ISLANDS		DOLOMITE WITH SHALY INTERBEDS	(BI)	
SILURIAN	UPPER	SALINA G		SHALY DOLOMITE		Local possibilities in parts of Kent County.
SILURIAN	UPPER	SALINA F		SHALY DOLOMITE, ANHYDRITE, SALT	(SF)	
SILURIAN	UPPER	SALINA E		DOLOMITE WITH SHALY INTERBEDS	(SE)	
SILURIAN	UPPER	SALINA D		ANHYDRITE, SALT		
SILURIAN	UPPER	SALINA C		SHALE, DOLOMITIC SHALE		
SILURIAN	UPPER	SALINA B		ANHYDRITE, SALT	(SB)	
SILURIAN	UPPER	SALINA A-2		DOLOMITE, SALT ANHYDRITE.	(SA2)**	
SILURIAN	UPPER	SALINA A-1		LIMESTONE, DOLOMITE, ANHYDRITE.	(SAI)***	
SILURIAN	MIDDLE	GUELPH-LOCKPORT		DOLOMITE	(G)	Potential in Norfolk County and parts of Oxford, Middlesex, Brant and Perth Counties. Possibilities in parts of Essex and Elgin Counties.
SILURIAN	MIDDLE	CLINTON		DOLOMITE, SILTY SHALE	(CL)	
SILURIAN	LOWER	CATARACT		SANDSTONE, SHALY DOLOMITE	(CT)	
ORDOVICIAN	UPPER	QUEENSTON		SILTY, SHALY DOLOMITE		
ORDOVICIAN	UPPER	MEAFORD-DUNDAS		SHALE DOLOMITIC INTERBEDS		
ORDOVICIAN	UPPER	COLLINGWOOD		SHALE		
ORDOVICIAN	MIDDLE	TRENTON		LIMESTONE	(T)	Potential in Essex County and parts of Kent, Elgin and Norfolk Counties. Possibilities in Haldimand, Welland and Lincoln Counties and parts of Wentworth, Brant and Lambton Counties.
ORDOVICIAN	MIDDLE	BLACK-RIVER		DOLOMITE, LIMESTONE, SHALY AND SILTY LIMESTONE	****	
CAMBRIAN				SANDSTONE	(CM)	
PRECAMBRIAN				IGNEOUS ROCKS	(PC)	

*(DRB), if (BB) not recorded individually i.e.(BB) is included in the Detroit River formation thickness.
(DRC), if base of (DR) is picked as the top of the chert.
**(SA2C)=carbonate, (SA2E)=evaporite
***(SA1C)= carbonate, (SA1E)=evaporite
****(WL)=Shadow Lake, the basal member of the Black River Formation, is occasionally recorded.

Blanc Formation was not picked, so that the Bois Blanc Formation [BB] was included in the thickness of the [DRB]. Hence cards with [DRB] were not used for the isopach map of the Detroit River Group. Sometimes the top of the [BB] was picked as the first occurrence of the chert associated with this formation (Brigham, 1971); for records where the first top below the undivided [DR] was designated as chert the code [DRC] was used. The distinction between [DR] and [DRC] was not used in further processing of the data.

ETF Elevation of the top of the formation in which the water was encountered (feet above msl).

DTF The depth of the water-bearing zone *below* the top of the formation (feet, always a positive number). Note that the well record does not provide information on the thickness of the water-bearing zone. The depth recorded is either the first significant water encounter in the vicinity of the recorded depth, or the depth at which most of the water is assumed to be entering the drill hole.

Figure 11 indicates the depth interval over which the water recoveries were reported and is subject to interpretation. It may indicate the thickness of the rock interval containing the water-bearing zone or it may represent the amplitude of the top of an undulating water-bearing zone of unknown thickness.

HWE Height of the water-bearing zone relative to the top of the Detroit River Group (feet, positive above the top, negative below the top). This information replaces DTF on some of the derived data decks. Since in the course of the study it was realized that the bulk of the water encounters were distributed around the top of the Detroit River Group, it became necessary to select cards on the basis of the height of the water-bearing zone relative to this formation top. Only on cards with the formation codes [D], [DR], [DRB], [DRC] or [L] was the DTF field so changed; for cards with one of the four Detroit River Group Codes the replacement consisted merely in changing the sign:

HWE = -DTF;

for cards with the Dundee code [D] the conversion had to include the thickness of the Dundee, since the Detroit River top was not coded on these cards, thus

HWE = FT - DTF

FT - Formation thickness (feet).

YR - Year in which the well was drilled.

SORTING AND ERROR CHECKING OF THE DATA DECK

The initial data deck was ordered by well number and the first step was to sort the data deck on the basis of formation name. This resulted in a deck in which cards with the same FN were grouped together, while the cards in each FN group retained their order by increasing well number.

With the cards arranged in this manner, an automated check was carried out—program CHECK (Table 4)—to remove any detectable clerical or computational errors. The possible errors which CHECK could detect were:

(i) ETF - EWE $\neq$ DTF, for EWE not a missing value (blank field)

(ii) FT < DTF, for FT not a missing value

(iii) SWE < EWE, for SWE not a missing value

(iv) Coordinates not identical for two cards with the same well number (provided the two cards were in the same FN group, hence consecutive in the file)

(v) ETF, FT, or YR not identical for two consecutive cards in the same FN group and with the same well number

(vi) Two successive cards completely identical (a not uncommon key-punching error)

(vii) Two successive cards with different well numbers, but identical coordinates (since two wells which are near each other may have the same coordinates, this occurrence was listed as a comment rather than as an error)

The commercial program package GPCP (General Purpose Contouring Program CALCOMP) was selected for producing all of the contour maps. Before contouring, a program PREGPCP was needed to read the data from the cards, and to pick the information needed by GPCP. This included the x- and y-coordinates and the mapped variable—either ETF for structure contour maps, or FT for isopach maps. PREGPCP punched these data out on a new deck, ignoring missing data, adding 1000 to all x-coordinates less than 500, and printing a warning message in those cases where two cards in succession had the same coordinates. Since GPCP was not designed to cope with the problem of two or more discrete data values at a single location, one of these cards had to be discarded and was removed by hand, necessitating an averaging of the mapped variable, the detection of an obvious error, or the discarding of a card with redundant information.

GEOLOGICAL MAPS

Structure contour maps were produced for the top of the Detroit River Group ([DR], [DRB], [DRC], [L]) and for the top of the Dundee Formation [D]; whereas isopach maps were prepared for the Dundee Formation [D], the Lucas Formation [L], and the Detroit River Group ([DR],

Table 4. List of Computer Programs

Program name	Input deck	Function	Printed output	Punched card output
SEEK	a) Original deck, sorted by formation name and well no.	To reject cards with a blank in EWE field	For each formation; number of cards punched, and number of cards deleted	EWE deck: only cards with values in EWE field
	b) As above	To reject cards with a blank in SWE field	As above	SWE deck: only cards with values in SWE field
	c) HWE deck = Output from HEIGHT	To reject cards with a blank in SWE field	As above	HWE-SWE deck: only cards with values in HWE and SWE fields
HEIGHT	a) EWE deck from formations DR, DRB, DRC, and L	Converts field DTF to height relative to the top of DR (or L, DRB, DRC) i.e. HWE = −DTF	As above	HWE deck: HWE replaces DTF
	b) EWE deck from formation D	As above, but now HWE = FT-DTF, and cards with blanks in the FT or DTF field are rejected	As above	HWE deck: HWE replaces DTF
CHECK	SWE, EWE, HWE deck or original data deck	Checks for possible errors in the data	List of all cards and comments on any errors detected	None
TABLE	SWE, EWE, HWE deck	Prepares a 2-way frequency table of occurrences of formation waters according to type and according to presence of a value for EWE, SWE, or both	Table and preliminary diagnostic data	None
WATYPE	HWE, HWE-SWE	Sorts data according to water type	Sorted list	Sorted deck
HISTOA	Hand-coded data, type or depth and frequency	To plot a histogram of the coded data	Input data and table of frequencies *Plotted output:* histogram	None
HISTOB	EWE, SWE, HWE; HWE-WQ decks;	To calculate frequencies and plot a histogram	Input data and table of frequencies *Plotted output:* histogram	None
SELECT	HWE-SWE; HWE-SWE-WQ;	Selects cards for which HWE falls within a specified range	Interval selected, number of cards punched, number of cards in original deck	Selected cards
PREGPCP	FT, for isopach map; ETF, for structure contour map; HWE-SWE decks for piezometric maps	Selects data for input to GPCP and produces decks in the required format. Flags cards with the same coordinates and eliminates cards with blanks in the field of the value to be mapped.	Prints a list of accepted, flagged, and rejected cards	Accepted cards in proper format for input to GPCP. Flagged cards corrected and added to the deck by hand.

[DRC]). Initially a series of each of these maps was produced, with different choices of the control parameters for GPCP. However, only that map which was judged the best of each series is presented in the main body of the report.

PIEZOMETRIC MAPS

For the preparation of the piezometric maps it was necessary to decide how to select from the cards with an entry for the elevation (SWE) the ones that best reflected the true piezometric head of the disposal zone or zones. Since the majority (85 per cent) of the SWE data came from the Detroit River Group and the Dundee Formation (Fig. 3), and McLean (1968) indicates that the disposal zone is located in the Lucas Formation, the study focused on the Dundee and Detroit River data.

Furthermore it was believed, and subsequently demonstrated (see Fig. 12), that a more rational selection could be made if the DTF entry for depth of water encounter were changed to HWE-the height of the water encounter relative to the top of the Detroit River Group. This change was made by program HEIGHT. It should be noted here that in this process the cards for the Dundee Formation which had no entry for formation thickness (FT) were deleted, since no value for HWE could be calculated. As a result, only 286 of the 419 Dundee Formation cards with SWE information were retained and the data deck at this stage was reduced to 1144 cards. Further details concerning the piezometric maps are contained in the main report, and as will become apparent, this loss of Dundee Formation data is of no consequence.