WATER RESOURCES DEVELOPMENT

FOR

HIGH ARCTIC COMMUNITIES

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by

Ralph Suk, B. Eng.

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AUTHOR: Ralph Suk, B. Eng. (McMaster University)

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ABSTRACT: This research indicates that present methods of water supply and sewerage for high arctic communities are inadequate from the point of view of health, aesthetics and economics. This thesis examines these present methods and their problems.

Field work was conducted in three communities of the Eastern Canadian Arctic. Data were collected with regard to, - the biological quality of the drinking water and raw water sources, the quantities of river water available, the soil conditions, the construction equipment and generating capacities of the small communities, water consumption, and the sizes and types of storage tanks within the communities.

In order to improve existing conditions, an entirely new method of water supply is developed in which water is intermittently distributed through electrically traced pipes to storage tanks within all the buildings. Computer programs are presented which will optimize the design on the basis of net annual cost. The related problems of water quality, power supply and sewerage are also examined and social, health and aesthetic effects are considered.

The results are novel in many respects: Distributed storage allows the use of very small diameter pipes and results in very low capital, construction and operating costs.

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This thesis would not have been possible without a great deal of help and co-operation from numerous other people. It is only possible to mention a few of them here.

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1 INTRODUCTION

1.1 Purpose

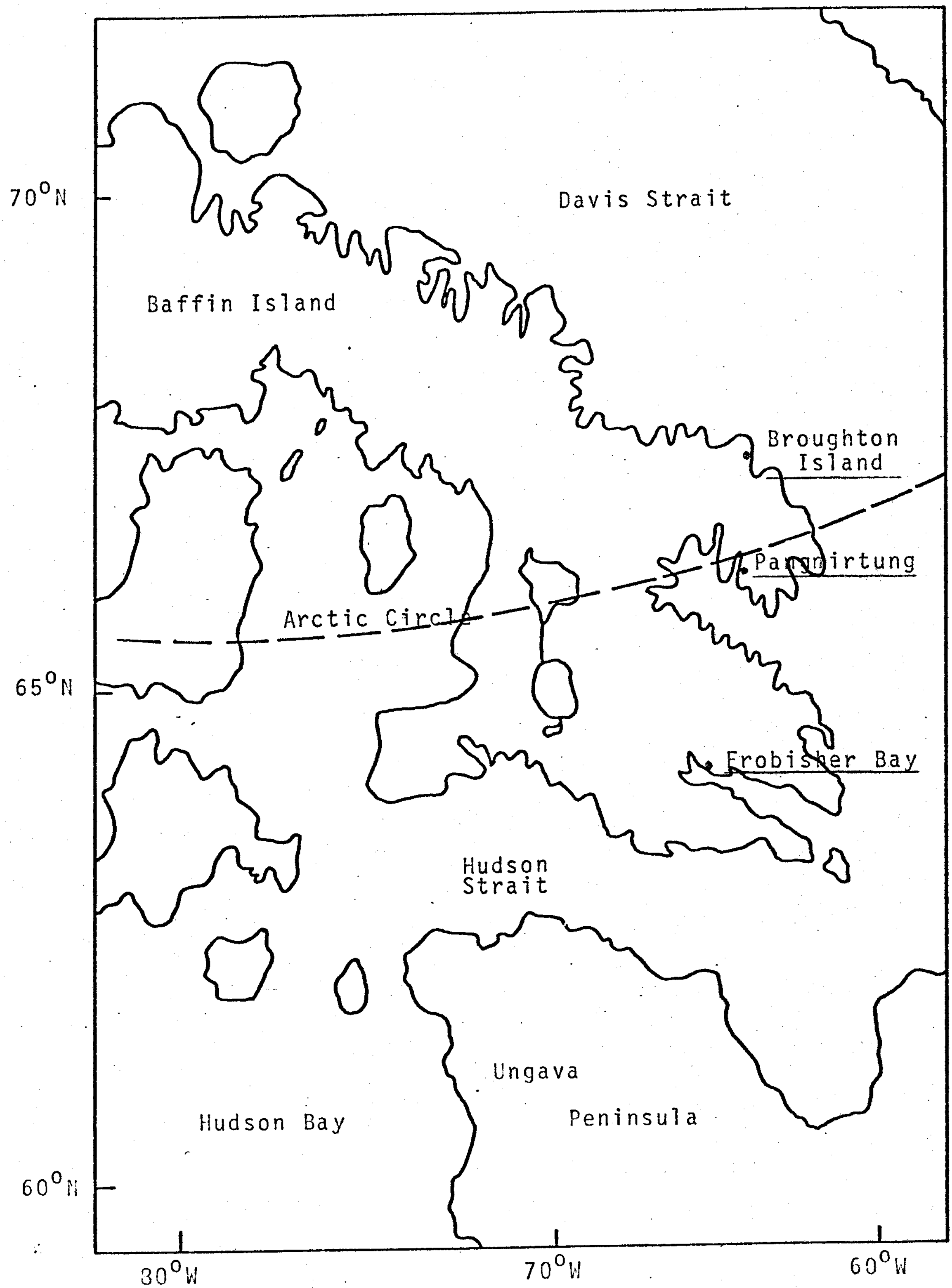
In southern communities the optimal design of water supply and sewerage systems is dependent on many inter-related variables including water quality, flow rates, pipe sizes, ground elevations, energy grades, and government regulations. In communities of the far north such designs are further complicated by permafrost, severe climatic conditions, thermal requirements, the high cost and scarcity of skilled labour, and the lack of a continuous water supply.

It is the purpose of this study to clarify these problems, to investigate the experience gained over the past fifty years towards solving them, and to present recommendations and computer programs which will aid in providing optimal or least cost solutions.

1.2 Scope of Study

This dissertation is the third in a series of M.Sc. studies in a research project undertaken in the Arctic by Dr. William James. The area of study was Eastern Baffin Island in the Northwest Territories, in and near the communities of Apex Hill, Frobisher Bay, Pangnirtung and Broughton Island (Fig 1). The earlier two studies (by

Fig. 1 THE BAFFIN REGION STUDY AREA



A.R. Vieira-Ribeiro and Lance Maidlow) presented computer simulation models and related computer methods for estimating river flows from arctic watersheds. Such models are useful for predicting river flows from a given set of physical conditions or for calculating maximum probable flows and water levels, and so on.

This thesis studies the problems of water distribution and sewerage in the communities of the high Arctic and develops new approaches and computer aids for the solution of the problems.

The data gathered on Baffin Island over the course of three years includes:

a) climatological data
b) stream flows
c) topographical data
d) present state of water and sanitation services
e) present conditions in housing
f) chemical and biological quality of raw water sources and domestic supplies
g) soils analysis

Streamflow records were obtained for the Apex River near Frobisher Bay, the Kuruluk River on Broughton Island and the Duval River near Pangnirtung. This was done in co-operation with Water Survey Canada and the Northern Canada Power Commission and the data were incorporated into their records. The water quality of these rivers and their sources was also measured.

An investigation of existing literature on Northern Engineering was made to supplement these data. Other workers, such as G.W. Heinke [47, 64], Amos J. Alter [2, 3], and Jack Grainge [43, 45] have carried out a number of extensive investigations into the existing conditions and problems of municipal services in the far north. Their work and that of the various engineering firms that have suggested design solutions [9, 38] was found to be invaluable as a basis and a guide for much of the work in this thesis. The problems of northern water supply and sewerage were also presented as design projects in fourth year Water Resources Engineering courses at McMaster University. The research, designs and cost analysis in these reports were of some assistance as well.

This study is the only one that encompasses hydrology, water quality, socio-economic factors, soil tests, and arctic construction practices and to offer validated computer optimization procedures.

1.3 Perspective

In assessing the value or benefits derived from a specified system of water distribution or sewage disposal, consideration should be given to health benefits [8], aesthetics, sociological implications [63], convenience, the environment, energy requirements and to water quantity and quality. Many communities of the high arctic experience serious difficulty in some or all of these areas [47].

The Government of the Northwest Territories has set standards for the quality and quantity of the water supplied to each consumer and for the methods of disposing of sewage and garbage. Table 1 summarizes the standards of water supply.

It is desirable to "clean up" the communities and yet to provide methods which are simple, dependable, operable and maintainable by local personnel. Energy requirements should also be carefully considered since energy supplies are both finite and expensive. Finally, care must be taken to protect the fragile northern environment from a population which is becoming rapidly more urbanized, industrialized, affluent and numerous [61].

A number of existing conditions thus influence the solutions to the problems of water supply and sewerage. These include the quality and quantity of the raw water sources, the topography, the characteristics of local soils, conditions in housing, existing installations, climate, the habits and attitudes of the people and the state of present technology. These are investigated as fully as possible before attempting to make any recommendations and designs, or determining procedures for optimal solution.

1.4 History

Traditionally, in the smaller communities of the far

TABLE 1

Summary of Water Supply Regulations

-Government of the N.W.T.-

Bacteriological Water Quality

a) The arithmetic mean of the coliform concentrations shall not exceed 1 per 100 ml for either the MPN[1] or the MF[2] method.

b) If, by either the MF or MPN method, the total coliform density is 9 per 100 ml or greater then additional samples shall be taken until at least 2 consecutive samples show the water to be of satisfactory quality.

Physical and Chemical Quality

Parameter	Upper Limit
Turbidity	5 units
Colour	15 units
Odour (T.O.N.)	3 mg/l
Chloride	250 mg/l
Flouride[3]	1.7 mg/l
Iron	0.3 mg/l
Nitrate	45 mg/l
Sulfate	250 mg/l
Total dissolved solids	500 mg/l

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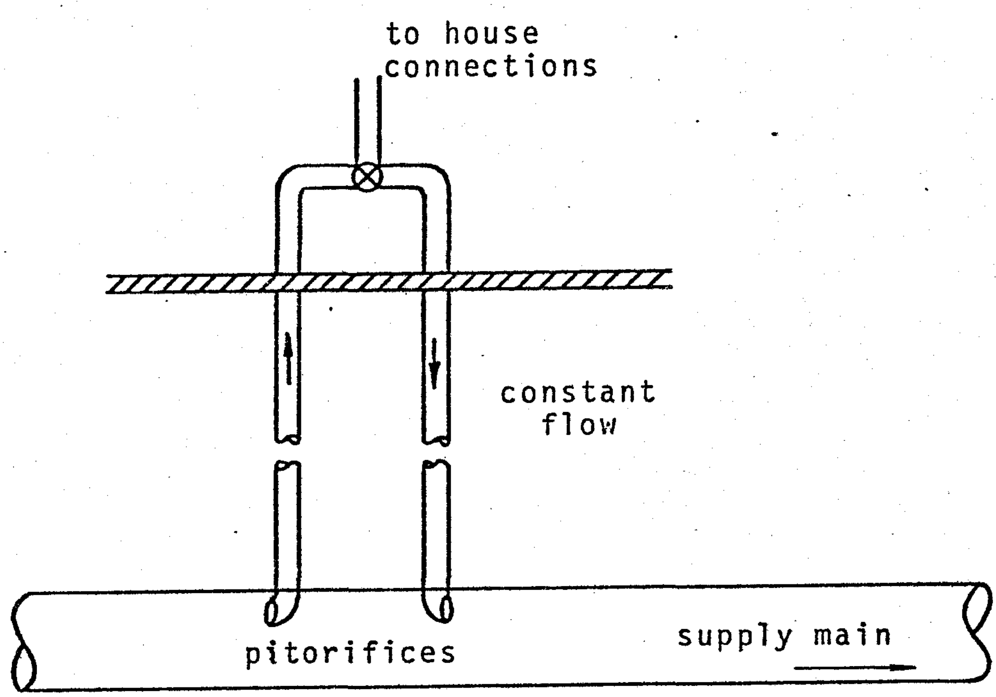
[1]The most probable number method.

[2]The membrane filter method.

[3]Flouridation is recommended with a residual of 1.2 to 1.5 mg/l.

north, the people have obtained water wherever they could find it and by whatever means available. Similarly, garbage and sewage was disposed of with least effort and little planning. Increased government assistance and the development of cold climate tracked vehicles has led to the method of hauling water by truck from the nearest available safe source and storing it within the houses. Dump sites were selected and garbage and sewage hauled to these locations for incineration or burial, usually without separation. In most small communities the Department of Public Works supplies the vehicles and maintains them, but the contract for labour is awarded to the lowest bidder. In the larger centres it is the responsibility of the Hamlet or Village to supply water and remove sewage and garbage. Policy has dictated that services should increase in quality as population increases. This is largely due to the fact that services become less expensive on a per capita basis for larger populations, since the total distance travelled per person served is less. The use of townhouses or apartment blocks is greatly advantageous with respect to supplying water services and heating. In larger centres the level of service is raised through the use of <u>utilidors</u> or <u>recirculating</u> water mains. <u>Utilidors</u> are enclosed conduits, usually raised, which carry most or all of the essential services from a central location to the buildings within the community. They utilize the heat lost from the heating supply to protect water and/or sewer mains from freezing. Recirculating systems add heat to the supply mains from heat exchangers and the supply is then fed to electrically traced service connections or to constant flow connections which may operate with pitorifices (Fig. 2).

Fig. 2 RECIRCULATING MAIN WITH PITORIFICES



Presently the N.W.T. Government is attempting to expand and upgrade services in both the large and small population centres, with more careful attention being given to providing proper treatment and waste disposal. For 1975 the budget for water supply and for garbage and sewage disposal is set at one hundred million dollars, to help achieve these goals [36].

2 BACKGROUND REVIEW

2.1 Methods of Water Supply for Communities in the High Arctic

2.1.1 Introduction

The conventional method of distributing water in buried pressure mains is not possible in the arctic environment since the ground is permanently frozen to great depths and thus the pipes freeze and rupture. Therefore a large variety of other methods have been, and continued to be, developed. A complete description and evaluation of all the methods can be obtained from various references [67, 49, 64, 2, 53, 4, 65, 47,1] and hence only a limited summary is undertaken in this thesis.

Many communities lack any water supply system at all and the individual is left to his own resources. Others employ systems encompassing several techniques, such as the settlement at Cape Dorset where water is supplied to a centrally located water storage tank through an electrically heated, insulated pipeline which is drained between supply periods. The water is then trucked from this tank to individual storage within the homes [69].

In many high arctic communities water is usually very scarce [26, 2, 74] and therefore systems which bleed off water are undesirable. The construction of utilidors is very costly in capital expenditure and maintenance costs [37], and the above-grade utilidors impede free movement. Trucking has also proven to be expensive and does not offer a satisfactory level of service at present [35, 38]. The two most promising low-cost alternatives may be recirculating systems and intermittent pumping systems. The design of these systems incorporates many variables such as insulation thickness, heat input and storage requirements. Therefore these designs are suitable for computer optimization. Such an optimization would help to determine the least-cost system without increasing the complexity of its construction or operation.

2.1.2 Trucking

The most common method of supplying water in small communities is through the use of water trucks [47]. Where roads are available and where these roads are clear in winter, tire trucks may be used. The latter are less expensive and faster than the tracked vehicles, but snow conditions, the lack of snow removal equipment and the rough terrain often necessitate the use of tracked vehicles in many communities.

The method of trucking water has several advantages: it does not require skilled labour and it creates employment opportunities.

There exist a number of disadvantages as well. The cost per gallon of water delivered is high since the vehicles are expensive to purchase and deliver [38, 35, 25]. Since the vehicles traverse very rough terrain in adverse weather conditions, they incur high maintenance costs [29, 25]. Furthermore the conditions of the terrain and climate impose very low maximum speeds on these vehicles, usually about 10 to 15 miles per hour, which further increases the cost of the delivered water [29].

Water costs are 2¢ to 6¢ per gallon depending on the haulage distance, and the speeds attainable. For Pangnirtung the cost is 2.2¢ per gallon and for Cape Dorset the cost is 5.5¢ per gallon [38]. Trucked water service usually requires that a man enter the house to fill an open container which is frequently replenished but seldomly cleaned [66, 29]. Water thus supplied is usually not treated and may become contaminated during or after distribution [29, see also Table 10]. In the event of vehicle breakdown, down-time is usually about three to six weeks (D.P.W. records, Frobisher Bay, 1974). Such vehicle breakdowns are quite frequent and since many communities have only one truck, there are often periods in which there is no water available other than that which the individual obtains from melting ice and snow. Finally, this method of service offers little fire protection, since the trucks are not equipped with fire hoses and are just as likely to be empty as full when a fire breaks out.

2.1.3 Recirculating Systems

Recirculating systems balance heat input with heat losses to prevent the distribution systems from freezing.

In the dual-main recirculating system a high pressure feed main supplies water to service connections which pass through the houses and out to a low pressure return main which collects the water for reheating. The occupants are then able to draw water from the service connection. The system is costly because piping is doubled and continuous heat input is required.

A later development uses a single main in which the velocity of the water is used to obtain a pressure differential across the service connection. This is done through the use of pitorifices, two of which are required for each connection, as shown in Fig. 2.

These systems are all able to use waste heat and conventional heat exchangers. Energy obtained directly from the combustion of fuel is five to twelve times less expensive than electrical energy [69]. However, since a stoppage of flow or heat input can be fatal to the entire network, electrical tracing tape or a similar insurance measure is sometimes recommended [2, 62].

The advantages of recirculating systems are that the pipe may be buried providing care is taken to prevent excessive movements of the foundations or pipe bedding. Also, adequate and controlled water treatment can be provided at the main pumping station and the need for domestic water storage tanks is avoided. If constructed and operated properly, maintenance costs can be low and thus help to justify the high capital costs. In addition, fire protection is easily furnished.

The disadvantages are the high capital costs and substantial energy requirements. It is important to optimize between insulation protection and heat requirements.

2.1.4 Intermittent Pumping

Intermittent pumping is another term for a pulsed water supply. In this method, heat is supplied to the distribution pipes only for relatively short intervals of time, during which water is pumped to storage tanks. Between supply periods the pipe remains unheated and is drained to prevent rupture. The pipe is normally insulated and placed near grade; and heat may be applied either to the water or the pipe or both [2]. For long lengths it is necessary to preheat the pipe and then keep it warm in order to prevent ice plugs. In most applications electrical heat has been used. Heating cables may be placed inside the pipe, the pipe may be used as a heating element or as return conductor, or tracing tape can be placed outside the pipe within a layer of insulation [2]. While these methods of pumping water have been used mainly at arctic work camps, DEW line stations and airbases, they have also seen application at villages such as Point Barrow, Alaska and Cape Dorset in the N.W.T. [2, 47]. It appears that in all applications water has been supplied only to centralized storage tanks from which some other form of distribution was necessary. Small service connections, filling storage tanks within the houses, have not been attempted by this method.

The disadvantages are that substantial movements of the pipeline occur, due to thermal expansion and contraction, and that insulation must be carefully protected from water and physical damage. Also, electrical energy demands are substantial and may require about one-fifth of the peak electrical demand of most communities. Electrical energy is expensive, but the waste heat from the generators, if conveniently available, can have valuable application in the heating of buildings and/or water supplies [64].

This system does offer reduced costs for a high level of service. Small diameter pipes may be used and little piping or heat is wasted for supplying return mains or completing loops. Decreases in overall pipe surface area also results in savings in energy costs. Where sufficiently large storage tanks are used, the total running time of the pipeline becomes relatively small and thus there are large savings in energy over alternate systems. Since pipes are usually empty and at ambient temperature, they do not seriously disrupt the frozen state of the ground, nor do they seriously corrode, and there is a great deal of slack time in which to make repairs or adjustments. Small diameter pipes are more easily repaired and replaced. Adequate and controlled treatment becomes attainable by this method and water wasted due to drainage is normally less than ten percent of the total amount supplied. Finally, storage tanks are already available in many northern homes and thus a pulsed system is more easily introduced. Capital costs are accordingly also reduced.

2.2 Water Quality

2.2.1 Introduction

To-day, an adequate supply of safe, clear water is not considered a luxury or convenience, but a necessity. Water quality is probably the most important factor in public health. Not only should it be safe to drink, but there should be an adequate supply for bathing and washing. In high arctic communities, disease has often been related to the poor quality or lack of water [30, 32, 8].

Data and observations presented in section 3.3.5 of this thesis confirm the poor standards of present water supply methods in the Arctic.

Considerable amounts of work have been expended in determining practical parameters and limits for the measurement of water quality. The Canadian Public Health Association periodically reviews developments in the science of water quality and sets standards and objectives [19]. The goals of these standards are that domestic water supplies be free from pathogenic organisms and their indicators and from deleterious chemical substances and radioactive materials; that it be palatable, aesthetically appealing and devoid of objectionable colour, odour and taste; and that it be not excessively corrosive or hard so as to damage distribution and storage facilities and domestic utensils, or waste soap [19]. The Canadian Public Health Association recommends that the World Health Organization International Standards (1963), European Drinking Water Standards (1961), and U.S. Public Health Service Drinking Water Standards (1962) be considered. The objectives and acceptable limits proposed by the above agencies are set out in tables 2 and 3.

2.2.2 Biological Quality

Raw water supplies usually contain large numbers of bacteria which are introduced from the soil and vegeta-

TABLE 2

Water Quality Standards

(Chemical Quality)

Parameter	Objective	Acceptable Limit
Colour (T.C.U.)[1]	less than 5	15
Odour (T.O.N.)[2]	0	4
Taste[4]	inoffensive	inoffensive
Turbidity (J.T.U.)[3]	less than 1	5
Temperature (°C)[4]	less than 10	15
pH[4]	6.5-8.3	6.5-8.3
Hardness (mg/l)[3]	80-100	
Ammonia (mg/l)[2]		.5
Flouride (mg/l)[1]		0.8-1.7

1 United States Public Health Service, 1967

2 World Health Organization International 1963

3 American Water Works Association recommended potable water quality goals, 1963

4 Canadian Public Health Association, 1972

TABLE 3

Water Quality Standards

(Bacteriological Quality)

Parameter	Objective	Acceptable Limit[1]	Max. Perm. Limit[1]
Total Coliform (MF method)[2]	no coliform	at least 95% of tests are negative for any 30 consecutive days and no count greater than 4 per 200 ml or 10 per 500 ml portion	at least 90% of tests are negative for any 30 consecutive days and no count greater than 6 per 200 ml or 15 per 500 ml portion
Total Coliform (MPN method)[3]	no coliform	at least 95% of tests are negative for any 30 consecutive days and no MPN greater than 4 per 100 ml	at least 90% of tests are negative for any 30 consecutive days and no MPN greater than 10 per 100 ml
Fecal Coliform (MF method)	no coliform	no coliform	no coliform

1 Where less than 10 samples are analysed in any 30 consecutive day period, no more than one sample should be positive for total coliform

2 The membrane filter method

3 The most probable number method

tion and many of which may be beneficial to man in aiding digestion and vitamin synthesis [56]. However, water is also a medium for harmful pathogenic bacteria and, when care is not taken, it may cause the spread of diseases such as gastroenteritis, infectious hepatitis, amoebic dysentry and typhoid [78, p. 289]. The most common of these in arctic communities are gastroenteritis and infectious hepatitis. The relationship between the occurrence of these diseases and the quality of the water supply has been explored by a number of researchers [2, 8, 31, 32] and was also investigated in the research carried out for this thesis as outlined in sections 3.2 and 3.3. Bad water has also been linked with the cause and spreading of numerous other diseases and maladies[78, p. 292] and therefore the disinfection and protection of domestic water supplies is good policy.

In order to monitor the bacteriological quality of water, indicator organisms are selected which will indicate the possibility of contamination by enteric, pathogenic bacteria. The accepted indicator is the coliform group which is defined as those bacteria which will produce gas and acid from one percent lactose peptone water within two days at 37°C. The coliform group includes some bacteria which are not enteric and, moreover, most are not pathogenic. However, the detection of coliform bacteria in significant numbers is a practical and efficient method of estimating the extent of water contamination. Where coliform testing gives positive results, more complex confirmed testing can be used to determine the exact type and source of pollution more carefully. The incubation of fecal coliform is often carried out in order to assess the type and the degree of contamination more carefully. Fecal coliform, which are a total coliform bacteria subgroup, specifically found in the feces of man and other warm blooded animals [56], may be separated by incubation on membrane filters in a selective broth at 44.5°C. The determination of fecal coliform numbers should not be used as a substitute for total coliform testing but only as an added indicator of fecal pollution. Table 3 gives the recommended limiting values of coliform concentrations in domestic water supplies[19].

The determination of total coliform is usually done by one of two basic methods. They are the long-used method of multiple tube fermentation, also called the "most probable number" technique and the newer, more efficient membrane filter method. A complete description of these techniques can be found in "Standard Methods for the Examination of Water and Wastewater" prepared and published jointly by the American Water Works Association and the American Public Health Association.

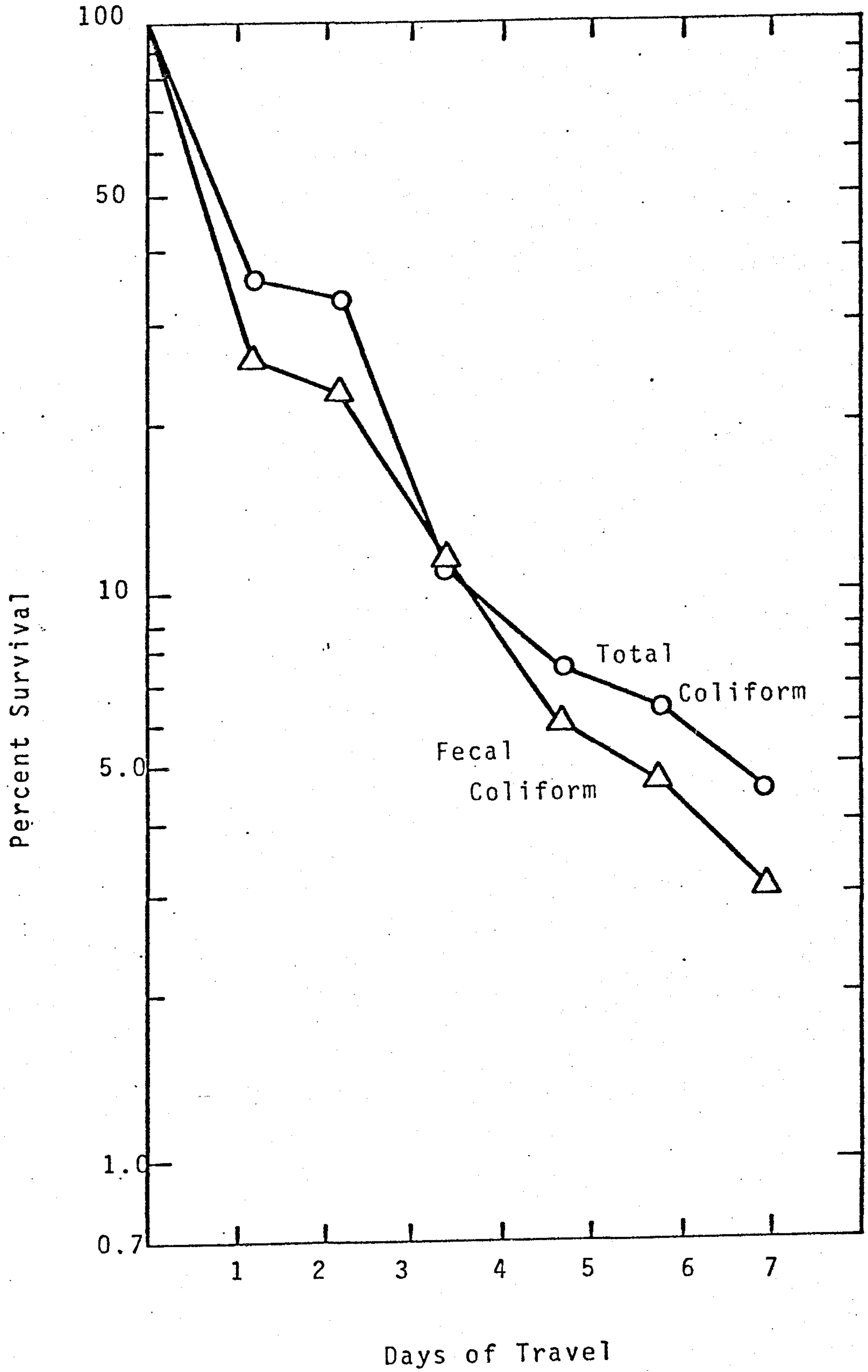
Since the numbers determined by each method usually differ somewhat [19], the standards are set according to the technique used (table 3). The membrane filter method usually gives lower results.

Both the total coliform group and the fecal coliform subgroup die when exposed to a cold, bright outdoor environment but not as rapidly as is often believed [31, 40]. Gordon [41] reports that there is approximately a ten percent survival after three and a half days in the Tanana River in Alaska during winter conditions. Figure 3 shows the time-survival rate of total and fecal coliform for the Tanana River.

2.2.3 Chemical Quality - An Overview

The chemical quality of water is important in assessing its suitability for drinking and for treatment and distribution. In the small arctic communities, the surface waters come mainly from snowmelt and are therefore usually of good quality. Teeter and Rosanoff [73] tested a large number of water sources for the DEW line stations in the Canadian Arctic and found only three that were unsuitable for domestic use. One was a tidal river which showed excessive salinity content and the other two were found to have excessive numbers of coliform bacteria. The only treatment required by most sources was filtration, to remove microscopic forms of plant and animal life, plus

Fig. 3 THE WINTER SURVIVAL OF COLIFORM IN THE TANANA RIVER OF CENTRAL ALASKA



chlorination. A few sources were recommended for water softening. E.W. Moore [57] investigated surface and groundwater sources throughout the Arctic in 1949 and concluded that the water sources in the Eastern Arctic tended to be of good quality and suitable as a source for domestic supplies while many sources in the Western Arctic often had high pH or some colour and odour which might complicate treatment somewhat.

In our own field work, in 1974, measurements were taken for alkalinity, hardness, pH, colour, turbidity and ammonia. The results are presented in section 3.3. The significance of these parameters and others in water quality determination is discussed in the following sections.

2.2.4 Alkalinity and pH

The alkalinity of water is its ability to neutralize acids. In natural waters it is usually principally due to the combined concentrations of carbonate, bicarbonate and hydroxyl ions, and is expressed in milligrams per litre (mg/l) of calcium carbonate ($CaCO_3$) equivalent. Alkalinity is desirable in domestic water supplies in order to prevent sharp changes in the pH by acting as a buffer. Chlorination tends to drop the pH and hypo-chlorination tends to raise it. Heating water may also cause a drop in pH. Such changes in pH can be very large and very sensitive when there is little or no alkalinity.

The pH of water is the negative log of the hydrogen ion concentration. Its value has a significant effect on the growth and survival of bacteria. Coliform bacteria thrive best at a pH of 6 to 7. Water of pH below 4 or greater than 9 is inhibitory or destructive to bacteria. Furthermore the pH is important in determing the corrosiveness of the water. Water with a lower pH value tends to be more corrosive to metals. The efficiency of chlorination is also a function of pH and is best done at lower pH values, with a pH of 8.3 being an approximate upper limit.

All things considered, it may be stated that alkalinity of 50 to 120 mg/l as $CaCO_3$ and a pH of about 6.5 to 8.3 after chlorination are preferred for domestic water supplies. (table 2)

2.2.5 Hardness

Hardness is a measure of the concentration of divalent metallic cations in the water, expressed as milligrams per litre of calcium carbonate equivalent. The principal hardness causing ions in natural waters are calcium and magnesium. Excessive hardness may be damaging to health [19] and also to kitchen utensils and the distribution system and it will cause soap wastage by the formation of calcium or magnesium stearate. However some hardness (say less than 100 mg/l) is not harmful and can be beneficial in providing water which is less corrosive and of good health quality.

2.2.6 Taste and Odour

Taste and odour are factors which may make water merely aesthetically unpleasant or they may give warning of water which is unhealthy. The degree of taste and odour is reported by a threshold number, which is the reciprocal of the dilution factor at which the taste or odour can no longer be detected.

Most water sources in the Eastern Arctic are free of any serious taste or odour [57, 73] especially the surface waters during the summer runoff period. However Teeter and Rosanoff [73] report some water sources as being acrid or earthy and reports from Broughton and Pangnirtung [26, 39] indicate that the water stored in the open earthen reservoirs there tends to become brackish and odourous during the winter storage period. Water in the reservoir at Pangnirtung, in the spring of 1974, was described as smelling like "someone had thrown a dead seal into it" [39]. Such odours might possibly be caused by the anaerobic decay of organic matter or by high contents of hydrogen sulfide or other sulfurous compounds from groundwater influxes.

2.2.7 Ammonia

Ammonia in water is not usually considered as an indicator of pollution unless large quantities exceeding 0.5 mg/l, measured in mg/l as nitrogen, are found [51]. Traces of ammonia are usually found in snow and rain and may also result from the biological degradation of protein and other nitrogenous matter in soil [51]. Large quantities may be detrimental to the chlorination of water and it can cause mild sickness, particularly in infants. The World Health Organization International sets an upper limit of 0.5 mg/l, while the American Water Works Association sets 0.05 mg/l as a desirable upper limit.

2.2.8 Nitrites and Nitrates

At least three species of aerobic bacteria, commonly found in soil oxidize ammonia to nitrite, [51, p. 134] and there are many species which oxidize nitrite to nitrate. The existence of the nitrite is usually of only short duration in the process and thus the nitrate content is normally higher than the nitrite content in natural waters. Nitrate is also found in rain water (about 0.3 mg/l) and small quantities of either nitrite or nitrate are not harmful. Large quantities (more than 5 mg/l) may be cause to suspect pollution, but is not a positive indicator thereof. In very large quantities (more than 50 mg/l) nitrates may become harmful, particularly if such water is used in infant feeding [51, p. 135]. Free chlorine will react with nitrite to produce nitrate:

$$NO_2^- + HOCl \rightarrow NO_3^- + H + Cl^-$$

However, in normal pH ranges, chloramines will not react appreciably with nitrites.

2.2.9 Colour and Turbidity

Like taste and odour, the amount of colour and turbidity is mainly a measure of aesthetic quality. Yellow or brownish colours are often present in groundwater sources due to high contents of organic compounds, but this does not indicate that such groundwater is unsafe to drink. Turbidity is usually the result of some suspended vegetal matter and clay and perhaps silt in more turbid water.

Colour can be measured by a number of comparative techniques. Probably the most common technique is the measure of light absorption within a restricted spectral band with a small portable spectrophotometer. The units thus measured are simply Units of Apparent Colour. An exact comparison of the values obtained by this method and visual methods is difficult, but the magnitudes are similar and a water source with less than 5 units of colour will be reasonably clear, regardless of the units chosen.

The degree of turbidity is commonly determined by measuring the amount of light scatter caused by a given sample of water. This measurement is also most easily performed with a spectrophotometer which must be calibrated against standard solutions of a substance such as formazin. Formazin is a milky white substance and the units thus measured are called Formazin Turbidity Units. Like colour, most measures of turbidity are similar and comparable.

2.2.10 Corrosiveness

A number of simple formulae or indices exist which are used to determine to what extent the water is corrosive or balanced. A balanced water supply is one which is neither exceedingly corrosive, nor will it deposit large amounts of calcium and magnesium scale. The desirable amount of calcium in water is a function of pH, temperature and alkalinity.

The most common index for determining the correct proportions of these factors is the Langelier Saturation Index which is:

$$LSI = pH + TF + CF + AF - 12.1$$

where TF is a temperature factor, CF is a calcium hardness factor and AF is an alkalinity factor. If the index is in the range of -0.5 to +0.5 the water is balanced. A lower value indicates that the water is excessively corrosive. A value of 0.0 to 0.5 indicates a water supply which will probably lay down a thin protective layer of calcium but is not encrusting. Values higher than 0.5 indicate a water supply that is exceedingly hard and encrusting. Appendix A shows the values of the required factors used in calculating the Langalier Index and shows a sample calculation for the Duval River at Pangnirtung in the N.W.T.

2.3 Water Resources

High arctic communities experience a relatively cold and dry climate. Temperatures remain at or below freezing levels eight months or more in a year and thus most of the precipitation is stored in the form of snow until the summer melt period. Runoff usually begins in late May or June and ceases again during September or October.

Since most of the runoff is derived from snowmelt, the flows in the smaller rivers are very dependent on the conditions of the snowpack and on daily weather variations. Early runoff periods are normally characterized by fairly high flows of water and ice. As the snowpack recedes with the passing of summer the flow within these rivers decreases and a proportionately higher portion will result from the thaw of ice within the active layer of the soil, groundmelt, the water stored in the depressions and the vegetal cover of the catchments or from the permanent ice fields in the higher parts of catchments such as the Duval River basin.

In general the small catchments of the high Arctic are fairly barren with a dispersed covering of lichens, mosses and sedges and perhaps some small flowering plants which grow in the thin soil of the active layer, which is only 2 to 3 feet thick. Most of the soil is derived from talus, outwash sediments and morraines, and is highly porous down to the surface of the permafrost. In general this permafrost surface may be quite smooth. Thus rainfall runs off rapidly with fairly small amounts of infiltration as opposed to interflow.

Many of the small communities of the high Arctic are located near small rivers which are used for summer water supply [47]. Thus the hydrology of small rivers in the high Arctic is important, especially in order to determine their adequacy for providing domestic water supplies, their flooding potential and also for their potential as a source of hydro-electric power.

A number of researchers have studied the hydrology of Arctic rivers [30, 55] and the former thesis [77] within this research project presented computer similation models for determining streamflow.

The Water Resources Branch of Environment Canada has also installed gauges on a number of rivers and the Atmospheric Environment Services maintains numerous meteorological stations throughout the Arctic. Environment Canada, in co-operation with the Northern Canada Power

Commission, is also studying the hydro-electric potential of some arctic rivers.

From the work conducted by other researchers and agencies and from our own field work, some general observations can be made about the hydrology of Arctic rivers:

a) The total amount of water running off, even in small catchments, is generally adequate for domestic water supply. For example, with twelve inches of runoff, the yield from one square mile is about 170 million gallons or enough for 4,800 people at 100 gallons per person per day (assuming adequate storage).

b) Large amounts of ice, in large pieces, are washed down during the early spring run-off period and this can provide problems of blockage, overtopping, scour and heavy ice pressure on engineering structures and river crossings.

c) The highest peak flows for design purposes are usually the result of heavy rainfall or a combination of heavy rainfall and snowmelt.

d) The response of stream levels to changes in weather conditions is very quick, unless the catchment contains considerable on-channel lake areas.

e) Depth of freezing in water is six feet or more and thus in all shallow rivers, lakes or reservoirs, freezing causes a concentration of impurities in the remaining liquid portion.

f) In the Arctic, at least several hundred horsepower of generating capacity would most likely be required to justify the capital cost of hydro-electric development. The power potential of water in HP can be expressed as:

$$\frac{Q \times H \times \gamma_1 \times K_1 \times K_2}{550}$$

where Q = flow in cubic feet per second

H = elevation in feet

γ = density of water (62.4 lbs/cu.ft.)

K_1 = pipe efficiency (approx. 80)

K_2 = turbine-generator efficiency (approx. .85)

Therefore for a minimum generating capacity of 100 HP , we require that

$$.07715\ QH > 100 \quad \text{or} \quad QH > 1296$$

If 500 feet of head is available we need a total average annual flow of at least 2.6 CFS. This would require the capability to store at least 400 million gallons of water over a 250 day, "no flow", winter period. Such storage is usually not available or very costly to develop.

g) Computer models can give a good design method for calculating daily stream flows from melt and rain events.

h) Infiltration and evapotranspiration losses are not significant.

In this project, 7 station years of records were collected. The methods and analysis are presented in subsequent chapters.

2.4 Water Treatment

2.4.1 Introduction

Complete treatment of water may consist of flocculation-coagulation, sedimentation, filtration, activated carbon treatment, disinfection, flouridation and adjustment for corrosiveness. These common processes are described below.

In 1971, of the 53 communities in the Northwest Territories, only the 10 largest communities had treatment plants and four more smaller communities employed chlorination [47].

2.4.2 Flocculation-Coagulation-Sedimentation-Filtration

The steps of flocculation, coagulation, sedimentation and filtration are all stages in a process toward producing a clear water. The first three steps are usually required in a water that has turbidity and/or colour which cannot be removed efficiently by simple filtration and chlorination. The above steps are also useful for removing large percentages of viruses and bacteria.

In the Eastern Arctic some groundwater sources can have considerable colour while some large turbulent rivers may have considerable turbidity due to clay and vegetal matter. However most sources are without appreciable colour or turbidity. These sources then require only some simple filtration.

2.4.3 Disinfection

Disinfection can be achieved by a number of methods which include chlorination, ozonation, radiation with ultra-violet light, and the use of chemicals other than chlorine. Apart from chlorination (or hypo-chlorination) these methods are probably not suitable for small communities in the high Arctic due to high costs and operational difficulties.

Chlorination is the most widely used method of water treatment. It has a large number of applications of which the single most important one is usually disinfection. However chlorine is also very effective for the removal of colour,taste and odour and for the protection of water against the future occurrence of contamination of colour, taste and odour. Chlorination disinfects through the production of hypochlorous acid (HOCl) and when ammonia is present, through the production of chloramines (monochloramine-NH_2Cl and dichloramine-$NHCl_2$). The hypochlorous acid disinfects much more quickly than the chloramines, but the chloramines have much longer retention times and thus provide longer lasting protection. The hypochlorous acid is produced either through the addition of chlorine gas (Cl_2) to the water:

$$Cl_2 + H_2O \rightarrow HCl + HOCl$$

or by the addition of hypochlorides such as calcium hypochloride:

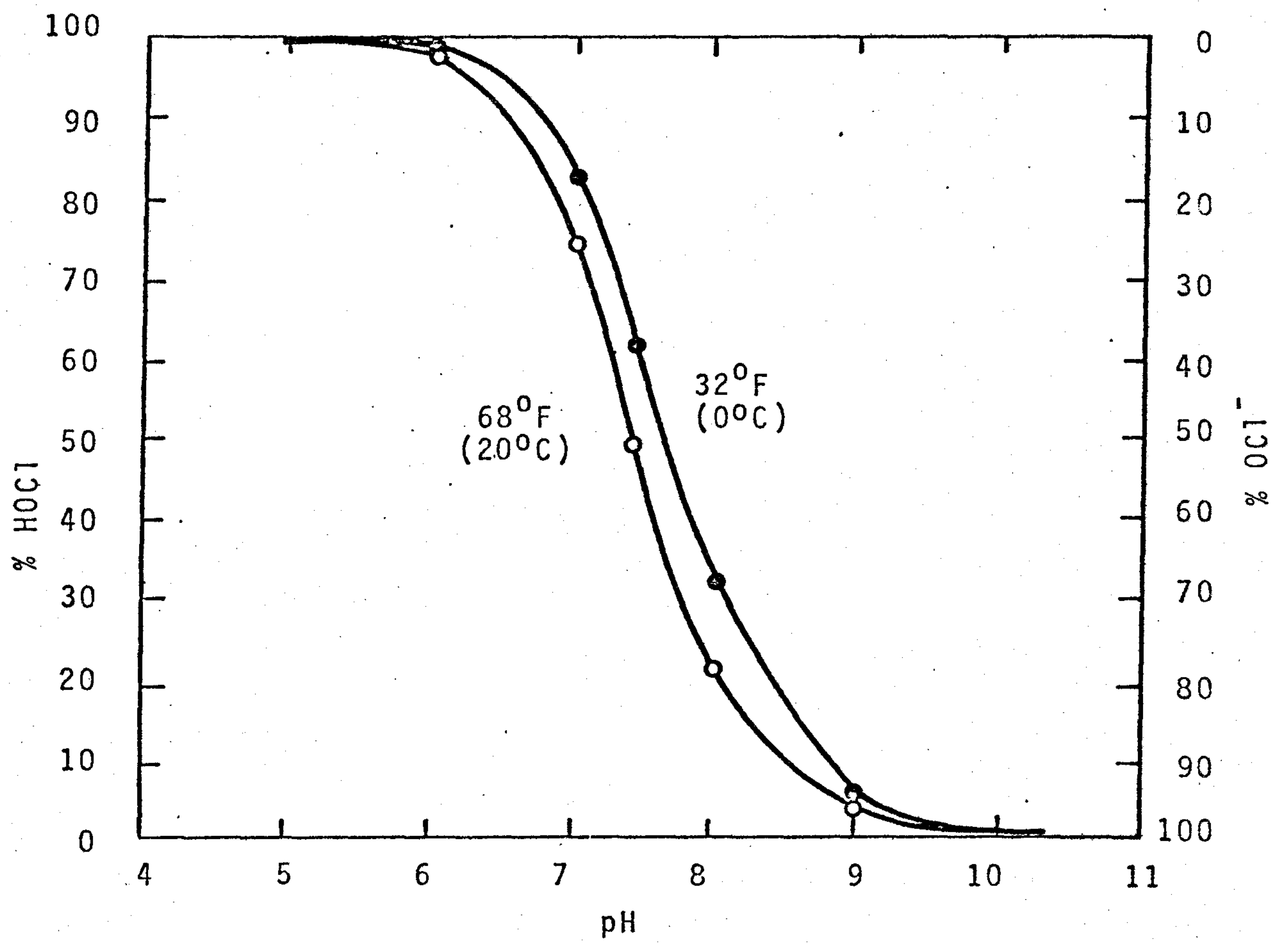
$$Ca(OCl)_2 + 2H_2O \rightarrow Ca(OH)_2 + 2HOCl$$

The hypochlorides are about four times more costly [78], but they are safer to handle and are simpler to apply. Both substances can be automatically metered into the water supply main. The rate of feed is largely dependent on the water quality. Enough chlorine must be added to react with substances in the water such as ammonia, iron and hydrogen-sulfide and then still give a residual of 0.5 to 2.0 mg/l HOCl. The residual obtained is also dependent on pH, since at higher pH values, increasing amounts of HOCl dissociate to H^+ and OCL^- (Fig. 4). Thus pH is usually maintained between 6.5 and 8.3, both for the maintenance of disinfecting power and the reduction of corrosiveness within the water. The maintenance of this pH range usually requires some alkalinity and perhaps the addition of a base where gas chlorination is used, since acid is formed by the reaction:

$$Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^-$$
$$\downarrow\uparrow$$
$$H^+ + OCl^-$$

The H^+ ions will deplete alkalinity to the extent of about

Fig. 4 THE DISSOCIATION OF HYPOCHLOROUS ACID VS. pH



1.1 mg/l alkalinity for every mg/l of chlorine added as Cl_2. Hypochlorites tend to increase the alkalinity but by insignificant amounts [19].

2.4.4. Other Treatments

Where chlorination is unable to improve taste, odour and colour, activated carbon in powder or granular form may be used. The powder is more efficient and less costly but requires good subsequent filtration. Superchlorination may also be effective, but this method would probably experience serious difficulties in application and monitoring in the small communities of the Arctic.

Flouridation is now widely carried out in water treatment facilities for its proven value in preventing dental decay. The application of a one mg/l flourine content is a simple and inexpensive procedure which is well recommended for arctic communities where dental hygiene is very poor and dentists very scarce.

2.5 Water Storage

Many communities of the high Arctic have sufficient water in summer when runoff from snowmelt and shallow lakes can provide abundant quantities; but for at least eight months of the year temperatures fall below freezing and the small rivers may stop flowing and shallow lakes freeze solid. Therefore an inherent problem of most water distribution schemes in the high Arctic is that of water storage.

Three basic methods exist for storing water. The first and usually the most expensive is to build on-channel storage, eg. the construction of a dam. In the Arctic, dam sites are difficult to develop, requiring the use of heavy equipment not available and difficult to maintain, and careful design for the stability and protection of the permafrost foundation.

The second method is construction of steel or wooden storage tanks. This method has the advantage that these tanks can be built in a central location, facilitating easy distribution, although the appearance of such tanks may not be appealing. Such storage tanks however have high initial and operating costs. Wardrop [9] estimated the costs for 500,000 gallon storage tanks for Pangnirtung to be $152,000 for wooden tanks and $192,000 for steel tanks, plus $15,000 p.a. for operation and maintenance. Transforming these 1972 costs to 1975, using a 6.5% annual rate of inflation and 10% for interest on borrowed capital over a lifespan of 20 years [37], we find that the cost per year of storage is 7.3¢ per gallon for the wooden tank and 8.5¢ per gallon for the steel tank.

A third method is the construction of an open reservoir. Many reservoirs in the Arctic may require an impermeable liner to prevent water from seeping out and to prevent poor quality groundwater from seeping in. About eight feet of the final depth should be allowed for ice and the bottom five feet should be kept clear for sedimentation.

The cost of an open reservoir is very difficult to estimate. In Pangnirtung the cost of the present 1,400,000 gallon reservoir (potable water) approached one million dollars [39] due mainly to the destruction of machinery on the large boulders and permafrost. On Broughton Island a reservoir of approximately 500,000 gallons was constructed for about four thousand dollars [26]. Neither reservoir has a liner and both are subject to losses from seepage and to contamination by groundwater influxes, which gives a brackish taste and foul smell to the water [26, 39]. Therefore a cost estimate is attempted herein for a lined reservoir using a building construction cost manual[42] and estimates in past reports by consulting firms [42, 9]. The estimates include excavation, blasting, hauling, liner, dewatering, drains to prevent uplift and sand, gravel and rock backfill to protect the liner (appendix B). For the construction of 3.0 Mill. gallon reservoir the cost was found to be 2.61¢ per gallon per year. This cost was estimated assuming that 50% of the volume required blasting and that labour and equipment costs in the Arctic are twice those of the south for 1975. With these assumptions the cost of storing water is approximately a third of that for building storage tanks.

Comparing the capital costs in appendix B to the reservoir construction costs estimated by the consultants [9], the former appear to be very high; perhaps much lower costs are possible. Evidently, then, storage in an open reservoir can be achieved for less than 2.61¢ per gallon per year.

2.6 Sewage Disposal and Treatment

Present methods of sewage disposal in the high Arctic include:

a) flushing kitchen wastes onto the ground amid the houses and into the streets

b) using plastic bags (honeybags) for the disposal of human wastes

c) holding tanks

d) gravity sewers

e) pressure sewers

f) vacuum sewers

A complete discussion of all the collection methods and their costs is beyond the scope of this thesis and can be found in the literature [3, 7, 20, 22, 38, 43, 48, 50, 60, 70, 76]. Only a few comments and observations are made here.

The most common method of sewage disposal presently employed for small communities of the high Arctic, is to flush the kitchen water onto the ground amid and beneath the houses and dispose of human wastes in green garbage bags called honeybags. These bags sit in a receptacle within the homes and are set outside or picked up for disposal when full or at set intervals. The method is simple but suffers from a number of problems and disadvantages. The honeybags tend to become mixed in with other garbage awaiting clean-up and they are often accidentally broken. The emptied bags tend to blow in the wind and are non-biodegradable. In summary, this method is not satisfactory. It is obviously hazardous to the health standards, aesthetic quality, and the environment of arctic communities.

Since piped sewage is very expensive [38] and skilled operators and servicemen are lacking in the small high arctic communities, the most feasible solution appears to be the use of individual holding tanks. These tanks hold all wastewater from the home and are pumped out by a service truck which then disposes of the sewage in a safe manner. There are a number of advantages:

a) The method is simple.
b) Conversion can take place gradually.
c) The level of service is comparable to that of conventional sewer systems.
d) Sewage treatment becomes feasible by trucking the wastewater to a sewage lagoon or treatment plant.
e) Employment is created for semi-skilled labour.

A large variety of methods are possible for the treatment of sewage in the Arctic. The more sophisticated methods are usually very costly and require skilled operators and close supervision. The various methods presently being employed include: no treatment at all; sewage lagoons, including aerated lagoons; chemical treatment; extended aeration sewage treatment; anaerobic treatment; dissinfection and dumping; and incineration. Of the above methods, the use of a sewage lagoon appears to be the most efficient and practical for small arctic communities [45]. They are capable of very effective treatment and are simple and almost foolproof to operate. Descriptions and discussions of the various methods of treatment and the advantages of sewage lagoons are not within the scope of this paper and may be found in the literature [1, 7, 20, 22, 29, 37, 38, 43, 45, 47, 49, 50, 53, 59, 60, 66, 70].

3 FIELD WORK

3.1 Introduction

The potential success of a water supply system, or sewage disposal system, for small high arctic communities is dependent on a number of factors which include:

a) the geophysical environment

b) the climate

c) the availability of a water supply

d) the quality of the raw water

e) the availability of storage

f) soil properties (foundation strength and suitability as construction material)

g) the accessibility of the community

h) energy resources and capacities

i) available construction equipment

j) the habits attitudes and capabilities of the people

k) costs

In the summer of 1974 field work was carried out in and near the communities of Frobisher Bay, Broughton Island, and Pangnirtung, in order to assess the above conditions and constraints. The results of the field work are set out in the following sections.

3.2 Methods

Chemical tests of the raw water sources were performed to help assess their suitability for drinking and to determine types of treatment that might be required. Tests were performed with the aid of a Hach Chemical Company DR-EL/2 Spectrophotometer. Samples were usually zeroed against distilled water and the instrument was standardized at the end of the field trip and some small corrections made to the data.

In order to assess biological quality, tests were performed for total coliform and fecal coliform. A portable Millipore incubator (No. XX63 001 00) was used along with the appropriate membrane filters and incubating broths.

In Frobisher Bay tests were performed in the laboratory at the water treatment plant with the permission and co-operation of the Northern Canada Power Commission. In Pangnirtung a small laboratory was set up in the Fire Hall, and in Broughton a room was shared in the Settlement Office. Sterile water was supplied by boiling for ten minutes or more and sterile bottles for the collection of samples were provided by the nursing stations. The nursing stations also provided alcohol for sterilizing instruments. For the coliform analysis, at least two samples of various sizes were incubated. The sample sizes depended on the coliform concentrations anticipated but were limited by the size of the sample bottles and filtering unit. Control tests with sterile water were frequently done in order to keep a check on procedure. Colonies were counted after about 22 hours incubation, but incubation was usually continued for several days since most bacteria were very dormant in the cold outdoor environment and growth was often delayed. Positive results for fecal coliform analyses of the natural waters were rare and therefore these tests were not done as frequently as those for total coliform.

Water was field tested from the Apex River near Frobisher Bay, the Duval River near Pangnirtung and the Kuruluk River near Broughton, in order to estimate the quality of raw water sources for typical communities in the Baffin region. Water was also tested from the various points in these catchments, such as glacial melt, groundwater seepage, and lakes, to help determine the source of any contaminants. Tests were performed throughout the summer to observe fluctuations in quality due to changes in climate and weather. Finally water from individual storage tanks in residences and other buildings, and from the water trucks, was tested to assess the effects of handling. In most cases, the coliform counts obtained were not large enough to be statistically reliable (less than 20). However, fine accuracy was not required, and such tests remain valid as indicators of raw water quality and its suitability for treatment and domestic use. Available water quality data were also gathered, particularly from the laboratory in the Water Treatment Plant in Frobisher Bay, and some cross correlations and checks were performed to determine the reliability of these data.

All water quality data are shown in the tables and figures of section 3.3 of this thesis.

Stream gaugings were performed with hand-held Ott-current meters (No. 10.150). Gaugings were performed for the Kuruluk River and the Duval River in order to determine the amount of shift that occurred in the stage-discharge curves from previous years. This change is caused by the fact that the installation of the water level recorders was not identical to that of previous years, boulders may move into the control section and because ice scour may have changed the bottom profiles of the rivers locally.

Soil samples were taken on Broughton Island and near Pangnirtung by digging pits about two feet square to permafrost depth and sampling the soil at various strata. At random intervals, the pits were continued to thaw depth and water seepage was observed. Where flowing sand or mud made excavation by shovel too difficult, samples were taken by driving a hollow section of steel pipe down to permafrost. The soil samples were flown back to McMaster University and analysed in the soils laboratory for particle size distribution and Atterberg Limits. These data are discussed in section 3.5

Data were also gathered on the cost and condition of available equipment and on the power generating capacities of the communities. Interviews were conducted in order to help assess local problems and attitudes. The above data are listed and discussed in sections 3.6 to 3.9

3.3 Water Quality

3.3.1 The Apex River

The Apex River catchment is small and narrow; about 12 miles long and 2 wide. It is located about two miles north of Frobisher Bay. About one half of the catchment area comprises rocky barren surface, and one half, thick matted lichens, mosses and sedges. The catchment also contains many shallow lakes of various sizes. At the time of sampling, runoff derived mainly from snowmelt.

The results of tests performed on the Apex River to determine its suitability for domestic use are shown in tables 4 and 5, and may be summarized as follows:

a) The coliform contamination that is present is most likely of soil or vegetal origin, since total coliform counts were always low and fecal coliform results were always negative.

b) Chemically, the water was of excellent quality for drinking. Ammonia, colour and turbidity were always low

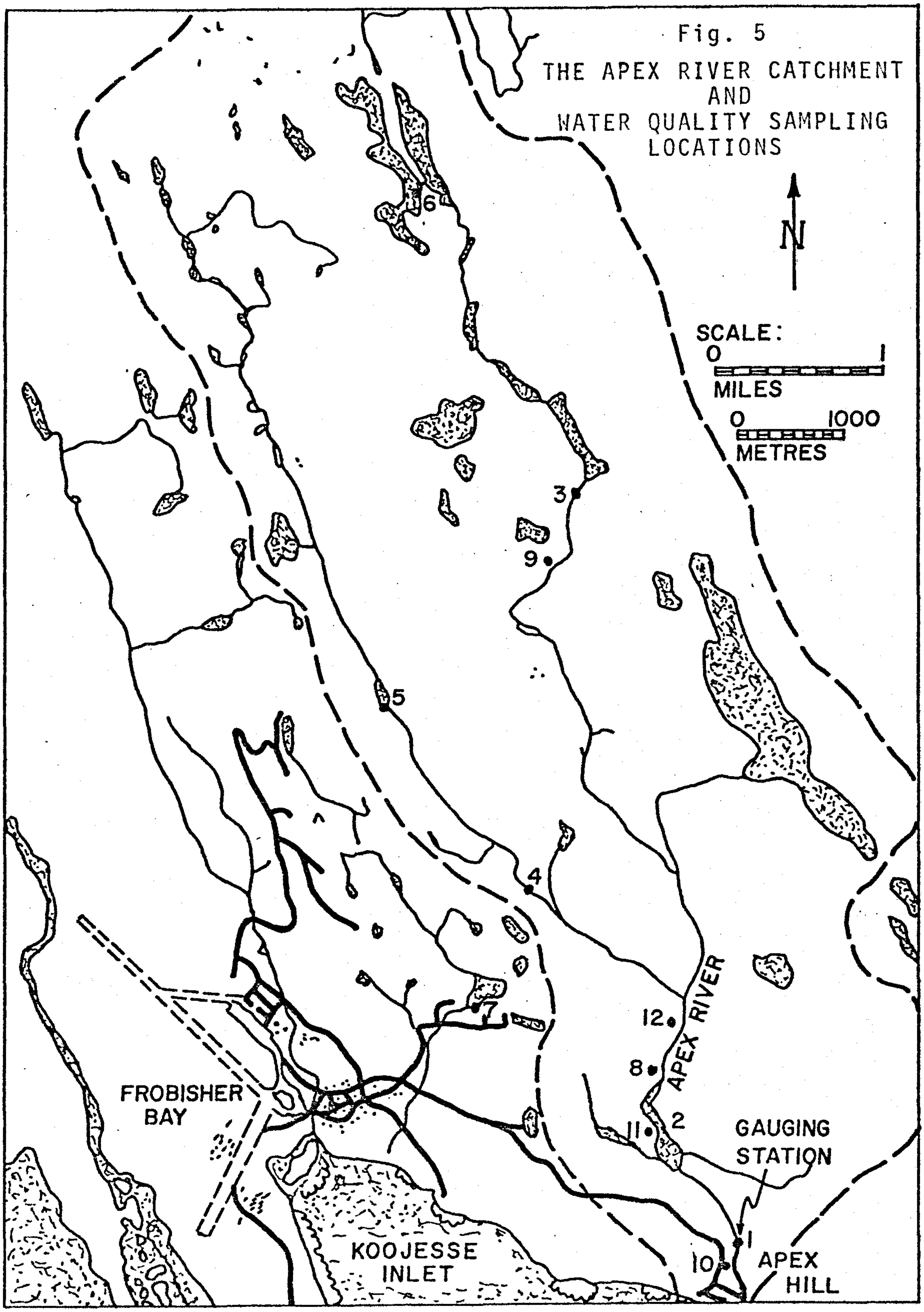


Fig. 5
THE APEX RIVER CATCHMENT
AND
WATER QUALITY SAMPLING
LOCATIONS
N
SCALE:
0
1
MILES
0
1000
METRES
1
2
3
4
5
6
7
8
9
10
11
12
APEX RIVER
FROBISHER
BAY
KOOJESSE
INLET
GAUGING
STATION
APEX
HILL

TABLE 4 APEX RIVER — WATER QUALITY

TEMPORAL DISTRIBUTION AT LOCATION NO. 1

Sample No.	Date and Time	Total Coliform per 100 ml	Ammonia mg/l as Nitrogen	Total Hardness mg/l as $CaCO_3$	Colour (U.A.C.)	Total Alkalinity mg/l as $CaCO_3$	pH	Turbidity (F.T.U.)	Flow Rate (C.F.S.)
*2	June 5, 74 1630	1		10	0	10			
8	June 6, 74 0930	0		10		10			
9	June 7, 74 1700	5	0.00						
13	June 8, 74 2200	2		10		10			
14	June 9, 74 2000	0	0.15		0	10		6	
18	June 10, 74 1400	0	0.39		0	9		4	
21	June 11, 74 1815	1	0.10		0	8		0	
29	June 13, 74 2400	0	0.12		0	10	7.0	0	
31	June 15, 74 1200	0	0.10		0	10	7.0	0	325
38	June 16, 74 2100	0	0.23		0	9	7.2	2	208
39	June 19, 74 2000	2	0.15			14	7.2	4	208
**41	June 20, 74 1400	1	0.00	10		20	7.2	3	138

10 tests for fecal coliform gave consistently negative results
*calcium hardness was 10 or 100% of total hardness
**calcium hardness was 8 or 80% of total hardness

TABLE 5 APEX RIVER — WATER QUALITY

SPATIAL DISTRIBUTION

Sample No.	Loc. No.	Description of Location	Date and Time (1974)	Total Coliform per 100 ml	Ammonia mg/l as Nitrogen	Total Hardness mg/l as $CaCO_3$	Calcium Hardness mg/l as $CaCO_3$	Colour (UAC)	Total Alkal. mg/l as $CaCO_3$	pH	Turbidity (FTU)
8	1	Apex River	June 6, 0930	0							
13			June 8, 2200	1	0.00						
29			June 13,2400	0	0.12			3	10	7.0	3
38			June 16,2100	0	0.23				9	7.2	2
28	2	Apex River	June 13,2300	0	0.00			1	10	7.0	3
36			June 16,2030	0	0.11					7.2	2
35	3	Apex River	June 16,1900	0	0.10					7.1	3
24	4	branch stream	June 13,2100	0	0.00			4	7	6.9	4
32			June 16,1430	1	0.27				7	6.7	5
23	5	small lake	June 13,2030	0	0.17			4	10	7.0	4
33			June 16,1500	0	0.26					6.9	3
5	6	large lake	June 16,1700	0	0.40				7	7.1	2
5	7	small lake	June 6, 1430	0							
10			June 8, 1930	0	0.08				10		
26	8	snowmelt	June 13,2200	0	0.00			0	3	6.6	0
6	9	snowmelt	June 6, 1500	0							
11			June 8, 1830	0	0.55	5		18	8		
35			June 16,1900	0	0.78				2	6.6	0
7	10	groundwater	June 6, 1645	0	0.24				10		25
12	11	groundwater	June 8, 2130	2	0.00	6	6	48	6		20
27			June 13,2300	1	0.52			8	10	6.5	7
37			June 16,2030	0	0.35				8	6.7	7
25	12	groundwater	June 13,2200	0	0.38				8	6.5	8

Fecal coliform counts were zero in all cases

No taste or odour was detected in any of the sources.

and there was no detectable taste or odour.

c) Alkalinity and hardness were also low (Approx. 10 mg/l as $CaCO_3$) and therefore the water is somewhat corrosive.

A spatial water quality survey was also performed in order to help determine where various types of water originate and to assess quality of the various water sources such as snowmelt and groundwater seepage. Figure 5 shows the locations of sampling points within the catchment and table 6 lists the results of the field survey. The results may be summarized as follows:

a) The direct snowmelt is free of any coliform but may be fairly high in ammonia and have a slightly low pH.
b) The groundwater tends to be fairly high in colour, turbidity and ammonia.
c) The quality of the water within the lakes is very similar to that of the river water.

3.3.2. The Duval River

The Duval River catchment was the largest of the catchments investigated. It has an area of about 39 square miles, and the longest river channel is about eleven miles. The river begins at an elevation of about 4,000 feet in the permanent ice fields of the mountains located on the periphery of the catchment. From the ice fields, the water flows steeply down to a large plain which is very rich in tundra vegetation and abounds in small tundra animals. The last two or three miles of the river, as it flows into Pangnirtung Fiord, are again steep and cascading. Most sampling was performed about one mile upstream of the fiord.

The tests for water quality, as summarized in table 6, indicate that the Duval River is good as a raw source of drinking water. Total coliform counts were in the range of zero to nineteen. Most of the coliform are likely to be of soil or vegetal origin, although some fecal contamination from the animal life of the region is also possible. There were no possible sources of direct human fecal contamination at the sampling point, apart from trapping or hiking parties. The chemical properties of the water were characteristic of melt from permanent snowfields. The water was slightly acid to neutral and of low alkalinity. It was without colour and of very low turbidity. Sampling at other sources or possible sources of domestic water supply indicated that water from groundwater springs was higher in colour and turbidity than the river water, with higher coliform counts (tables 9, 10) and with some slight earthy odour and taste. A sample from a shallow lake which drains slowly and directly into the Duval River showed that this water was high in coliform and contained a visible amount of colour and turbidity as well.

TABLE 6

DUVAL RIVER - WATER QUALITY

Sample No.	Date and Time	Total Coliform per 100 ml.	Total Alkalinity (mg/1 as $CaCO_3$)	pH	Flow Rate (C.F.S.)
22	June 13, 74 0900	0			173
42	June 26, 74 0130	5			165
43	June 26, 74 1930	11	6.0	7.1	176
66	July 27, 74 1140	1			153
72	Aug. 6, 74 2000	2		6.9	148
74	Aug. 7, 74 2045	4		7.0	157
75	Aug. 8, 74 0115	3		7.0	159
76	Aug. 8, 74 0830	4	4.0	6.9	143
77	Aug. 8, 74 1215	3		6.8	138
78	Aug. 8, 74 1615	6		7.0	138
79	Aug. 8, 74 2015	19		7.0	167
85	Aug. 13, 74 1645	14		7.0	177
87	Aug. 14, 74 1215	14			193
88	Aug. 15, 74 1220	0			165
90	Aug. 16, 74 2030	16			186
92	Aug. 19, 74 1300	2			149
93	Aug. 19, 74 2015	7			175
96	Aug. 23, 74 1610	1			132

Colour was 0 in samples 43 and 85.
Ammonia was .005 in sample 43.
Turbidity was 3 in samples 43 and 85.

3.3.3 The Kuruluk River

The catchment for the Kuruluk River, (called the Broughton River or Broughton Creek in former theses) is the smallest of the three catchments studied. It has an area of about twelve square miles and a longest river channel length of about six miles (Fig. 6). There are large areas of mud and (almost) stagnant water. The hills are very rocky with little vegetation while the flat areas and the foothills are well covered with mosses and lichens. The catchment is frequented by a flock of ravens. At the time of sampling, runoff derived from a combination of snowmelt, rainfall and groundwater seepage.

The total coliform counts ranged from zero to fourteen and the water was of very low alkalinity and was slightly acid (table 7). The coliform were probably of soil or vegetal origin although some fecal coliform of animal origin was also possible. There was no source of human fecal contamination at the sampling point. Chemically the water is suitable for drinking but is quite corrosive in its natural state.

3.3.4 Seasonal and Diurnal Variation of the Biological Quality of Surface Waters

Many factors contribute to the concentration of coliform in surface waters. The chemical quality of the water, the water temperature, the air temperature, the amount of sun-

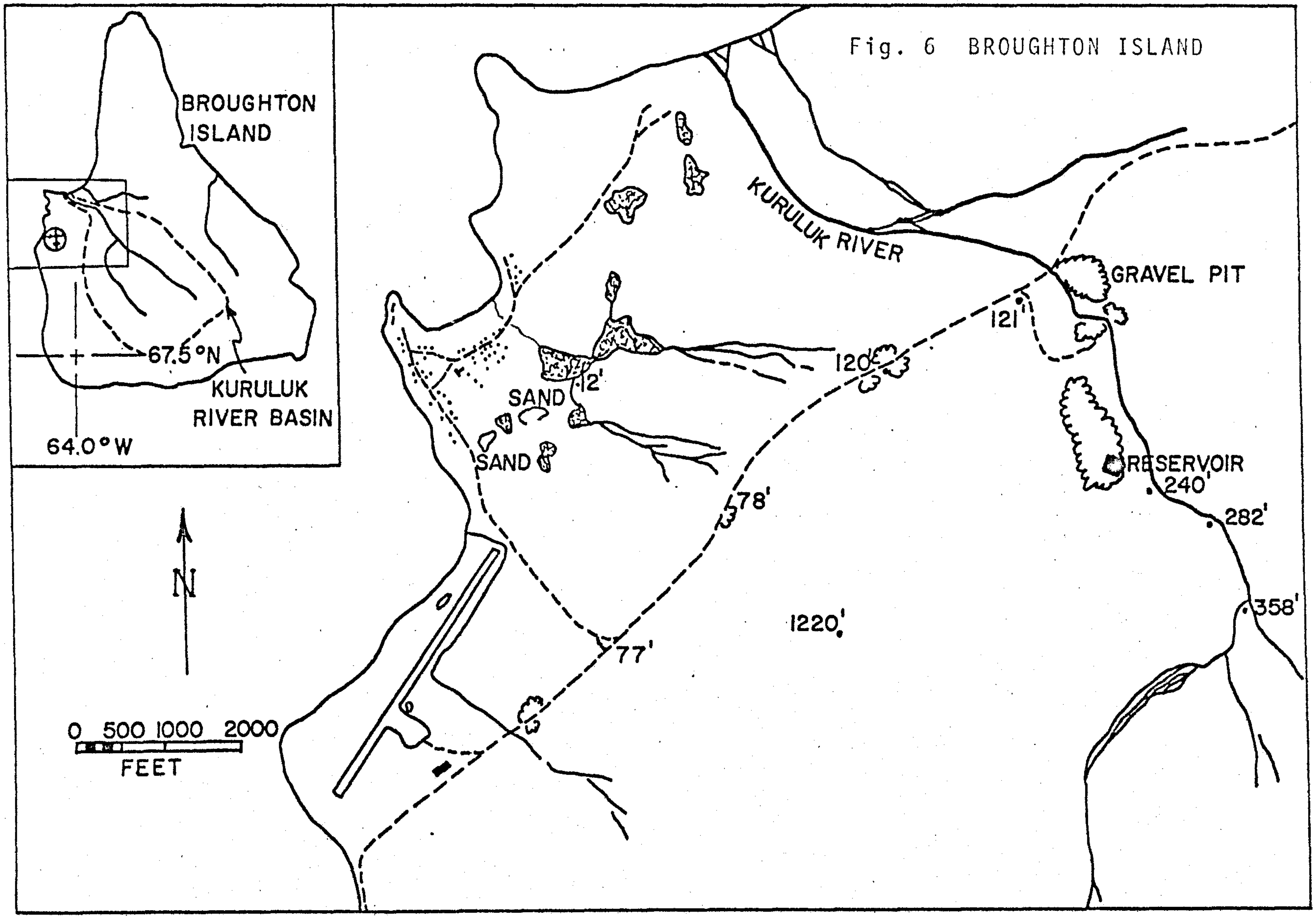


Fig. 6 BROUGHTON ISLAND

TABLE 7

KURULUK RIVER - WATER QUALITY

Sample No.	Date and Time	Total Coliform per 100 ml.	Total Alkalinity (mg/1 as $CaCO_3$)	pH	Flow Rate (C.F.S.)
46	July 9, 74 1300	2	3	6.7	7
47	July 10, 74 2130	1	3	6.5	7
49	July 12, 74 1300	2	3	6.6	7
50	July 13, 74 2200	4		6.5	35
51	July 14, 74 1800	2	3	6.7	159
57	July 16, 74 1550	0	3	6.6	311
58	July 18, 74 1700	1			202
60	July 20, 74 2000	4			103
63	July 26, 74 1615	5		6.5	28
68	July 28, 74 1630	11			7
70	July 29, 74 1650	14		6.5	7
71	July 30, 74 1650	4			7
86	Aug. 10, 74 1015	0			7
97	Aug. 23, 74 1430	0			7

Turbidity was 4 in sample 57.
Ammonia was 0.0 in samples 46 and 47.

light and the smount of rain are some of the factors that affect the rate of growth, the rate of entry and the period of survival of coliform bacteria. Therefore a smooth, continuous and exactly reproducible plot of variations in coliform concentration cannot be expected. Only trends can be measured.

A plot of all coliform results (Fig. 7) indicates that levels tend to be highest in late July or early August. This may be due to the fact that this is the warmest part of the year and the period of peak growth and activity in vegetation and animals. The warmer temperatures produce increased over land flows and thus lead to peak bacteria levels

A plot of diurnal variation of coliform levels performed August 7 to 9 for the Duval River near Pangnirtung (Fig. 8) shows that high coliform levels tend to occur with high river levels. The Duval River at the time of sampling was being fed mainly from the permanent icefields in the distant mountains since all snow cover had melted and it had not rained for many days. The peak flows were thus caused by peak daily temperatures. Therefore the higher coliform levels might result from faster travel times, warmer water temperatures and by increased numbers of coliform being washed down by a rising river level.

3.3.5 Observations of the Quality of Domestic Water Supplies

Fig. 7 SEASONAL VARIATION OF TOTAL COLIFORM IN ARCTIC RIVERS

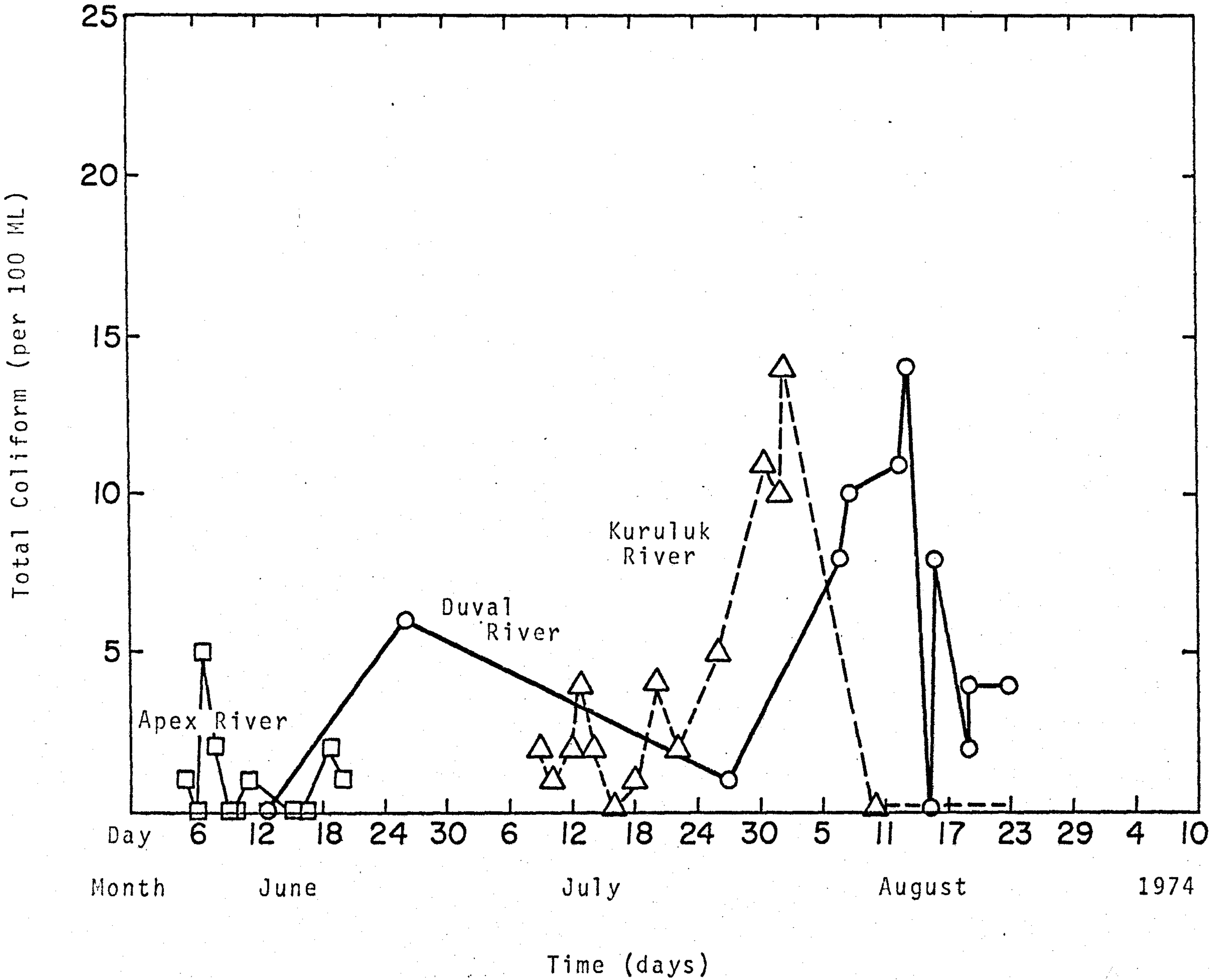
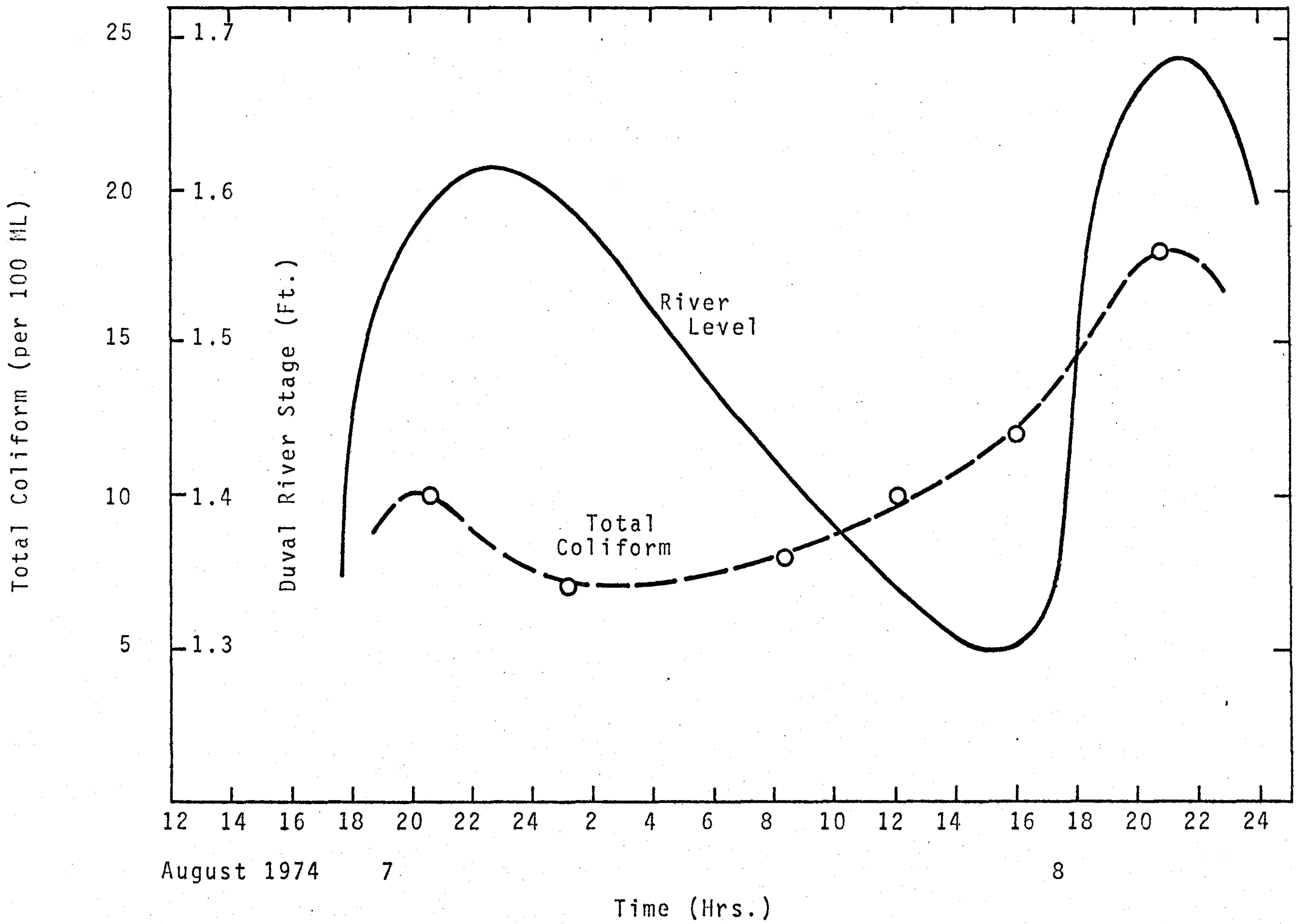


Fig. 8 TOTAL COLIFORM VS. WATER LEVEL IN THE DUVAL RIVER



Tests of domestic water sources and supplies within the dwellings are summarized in tables 8, 9, 10. From the sampling that was performed in three communities on Baffin Island the following observations are made:

a) The chemical quality of the surface water in the high Arctic tends to be very suitable for domestic use.

b) Surface waters are in general very soft with low alkalinity and with pH in the range of 6.5 to 7.2. Thus they are fairly corrosive to metals.

c) Coliform concentrations in surface waters are often above accepted limits for drinking water. Although these coliform are not likely to be pathogenic, disinfection is nevertheless warranted.

d) Groundwater or springwater tends to be high in colour and turbidity with coliform concentrations that are higher than those of raw surface waters.

e) Lakes are of variable quality. Small lakes with long retention times tend to be of poor quality.

f) The results of coliform tests performed randomly for domestic storage and in houses where illness was reported (table 10) clearly indicate that the present method of trucked distribution and storage within open containers leads to dangerous contamination of the water.

In Broughton, in July of 1974, it was reported by the nurse that there were water related illnesses in the settlement. There was at least one case of infectious

TABLE 8

AVERAGED VALUES OF WATER QUALITY

(No. of samples tested)

LOCATION SAMPLED QUALITY PARAMETER	DUVAL RIVER	APEX RIVER	KURULUK RIVER	SNOWMELT	GROUND-WATER	APEX LAKES	DUVAL LAKES	PANGNIRTUNG RESERVOIR	PANGNIRTUNG SPRING
Total Coliform	6.2 18	1.0 12	3.6 44	0.0 5	0.6 5	0.0 4	114.0 2	23.7 4	10 3
Fecal Coliform	0.0 2	0.0 12	0.0 3	0.0	0.0 4	0.0 5			
Ammonia	0.01 1	0.14 9	0.00 2	0.44 3	0.30 5	0.24 3			.65 1
Total Hardness		10 4		5 1	6 1				
Total Alkalinity	5 (2) 2	11 9	3 5	4 3	8 5	9 3		6 1	6 1
Colour	0.0 2	0 7		6 3	28 2	4 1		5 2	30 2
Turbidity	3 2	2 8	4 1	0 3	13 5	3 3		7 1	13 2
pH	7.0 8	7.1 5	6.6 8	6.6 3	6.6 5	7.0 3	7.0 1	6.9 1	6.7 2

TABLE 9

BIOLOGICAL TESTS OF DRINKING WATER

Sample No.	Date and Time	Locale	Source of Water	Sample Source	Total Coliform (per 100 ml.)	Fecal Coliform (per 100 ml.)
15, 16 17	June 9, 74 2000	Frobisher Bay	N.C.P.C. water treatment plant	water trucks	0	0
19	June 9, 74 1200	Pangnirtung	Duval River	Hotel	11	0
98	June 23, 74 -	Strathcona Sound	small lake	mining camp	50,000+	5,000+
45	June 27, 74 1230	Pangnirtung	Duval River	reservoir	42	/
30	June 14, 74 1830	Broughton Island	Kuruluk River	Colorado House	92	0
**48	July 10, 74 1700	Broughton Island	Kuruluk River	Colorado House	0	/
+55	July 15, 74 1400	Broughton Island	Kuruluk River	house storage	200	4
Δ56	July 15, 74 1400	Broughton Island	Kuruluk River	house storage	224	50
54	July 15, 74 1400	Broughton Island	Kuruluk River	house storage	20	8
67	July 27, 74 1255	Pangnirtung	Duval River	reservoir	17	/
73	Aug. 6, 74 2000	Pangnirtung	Duval River	reservoir	6	/
80	Aug. 9, 74 1415	Pangnirtung	hill to the south of Pang.	Spring water	8	/
89	Aug. 15, 74 1600	Pangnirtung	spring water	water pipe	12	/
69	July 29, 74 1330	Broughton Island	Kuruluk River	water truck	12	/

** This water storage had been recently treated with chlorine.
+ Infectious hepatitis was diagnosed within this family.
Δ Gastro-enteritis was diagnosed within this family.

TABLE 10

SELECTED TESTS FROM THE RECORDS OF N.C.P.C., FROBISHER BAY, INDICATING COLIFORM CONTAMINATION OF WATER SUPPLIES

Location of Sample	Description	Source	Date Collected	Date Tested	Total Coliform (per 100 ml)
Pangnirtung	private dwelling	reservoir	Jan. 3, 74		60
Clyde	private dwelling	river	Jan. 5, 74		500+
Broughton Island	private dwelling	ice melt	Jan. 7, 74		20
Arctic Bay	private dwelling	private	May 22, 74		20
Broughton Island	school	lake	April 17, 74		100
Resolute	private dwelling	private	June 4, 74	June 5, 74	60
Grise Fiord	water carrier		June 13, 74	June 19, 74	500+
Hall Beach	water carrier	lake	June 5, 74		50
Igloolik	private dwelling		June 26, 74		30
Grise Fiord	private dwelling		July 22, 74	July 23, 74	500+
Broughton Island	private dwelling	Kuruluk River	July 1, 74	July 2, 74	500+
Pangnirtung	swimming pool	Duval River	July 4, 74	July 5, 74	500+
Grise Fiord	private dwelling		July 22, 74	July 23, 74	190
Hall Beach	private dwelling	lake	July 24, 74	July 25, 74	120
Resolute	private dwelling	lake	July 18, 74		500+
Igloolik	private dwelling				500+
Hall Beach	water truck	lake	June 5, 74		50
Lake Harbour	private dwelling		May 23, 74	May 29, 74	10
Grise Fiord	nursing station		Aug. 9, 74		110
Arctic Bay	private dwelling		Aug. 14, 74		110

*31% of all tests performed gave positive coliform results.

hepatitis (which was also present at the DEW line station on Broughton Island at this time) and there were two households where gastro-enteritis was suspected. Samples of the water supply were taken from the household suffering infectious hepatitis, from one of the households with gastro-enteritis, and from a third household where, because the water supply had shown a positive coliform result previously, the storage container had been cleaned. In all three cases there were positive results for both total coliform and fecal coliform (see samples 54, 55, 56-table 9). Tables 9 and 10 indicate that contamination of the water supply in arctic communities, by pathogenic organisms, is quite possible, or even probable, with present distribution practices.

3.4 Water Quantity

Daily streamflows were measured for the three rivers with the co-operation of the Water Survey Branch of Environment Canada, who supplied the automatic Stevens A-7 water level recorders. Climatological data were obtained by placing automatic temperature recorders and by consulting the appropriate agencies which included Atmospheric Environmental Services in Frobisher Bay and Pangnirtung, and INSTAAR[1], the Hudson Bay Company and the U.S. Department of Defense (the DEW line station) on Broughton Island.

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[1] Colorado State University: Institute for Arctic and Alpine Research.

Calibration curves for converting water level data to streamflows were obtained through the use of three computer programs written by the author. The first program, GAGE, converts velocity depth profiles to streamflows. Then CURFIT determines polynomial curves of any degree by the method of least mean squares and plots the results. Finally LIST interpolates the resultant curve and prints a table of streamflows for water levels at 0.01 foot intervals.

The water level records were converted by the Water Survey of Canada with curves that they obtained in a similar manner. Results obtained by the author were transmitted to the Water Survey of Canada, and these rating curves have now been officially adopted. The three stations have now been permanently taken over by the Water Survey of Canada.

The total amounts of runoff for 1974 were relatively low since an unusually small amount of snowfall occurred in the Franklin District of the Northwest Territories during the 1973-1974 winter. The records of Atmospheric Environmental Services show that for the 1973-74 winter period there was an accumulation of 81.7" of snow on Broughton Island and 61.1" at Frobisher Bay, whereas the normal accumulations are 106.2 and 97.2 inches respectively. However, peak flows were nevertheless very similar to peak flows in previous years and the total amount of runoff was well in excess of the total requirement for the domestic needs of the communities.

3.5 Soils Data

On Broughton Island, soil samples were taken at various locations and at various depths. Fig. 9 shows the locations of the sampling sites for Broughton Is. In Pangnirtung, samples were obtained from the inside northern bank of the reservoir in order to estimate permeability, and from the sand pit located to the south of the reservoir.

The results indicate that a large variety of soil types with various gradations and permeabilities are available. Clean uniformly graded sand is available from the beaches in both locations. Large deposits of gravel and silty clay can also be located. The clay content of one sample from Broughton Island was 30%. Such soil deposits are not unexpected for mountainous regions which have undergone numerous glacial periods. There are a large variety of soil types present and except for beach deposits, they are usually well mixed. Table 11 summarizes the results obtained for Broughton Island.

3.6 Equipment Inventories

The construction of new facilities for water distribution and sewage disposal will require the use of heavy construction equipment that is not presently, generally,

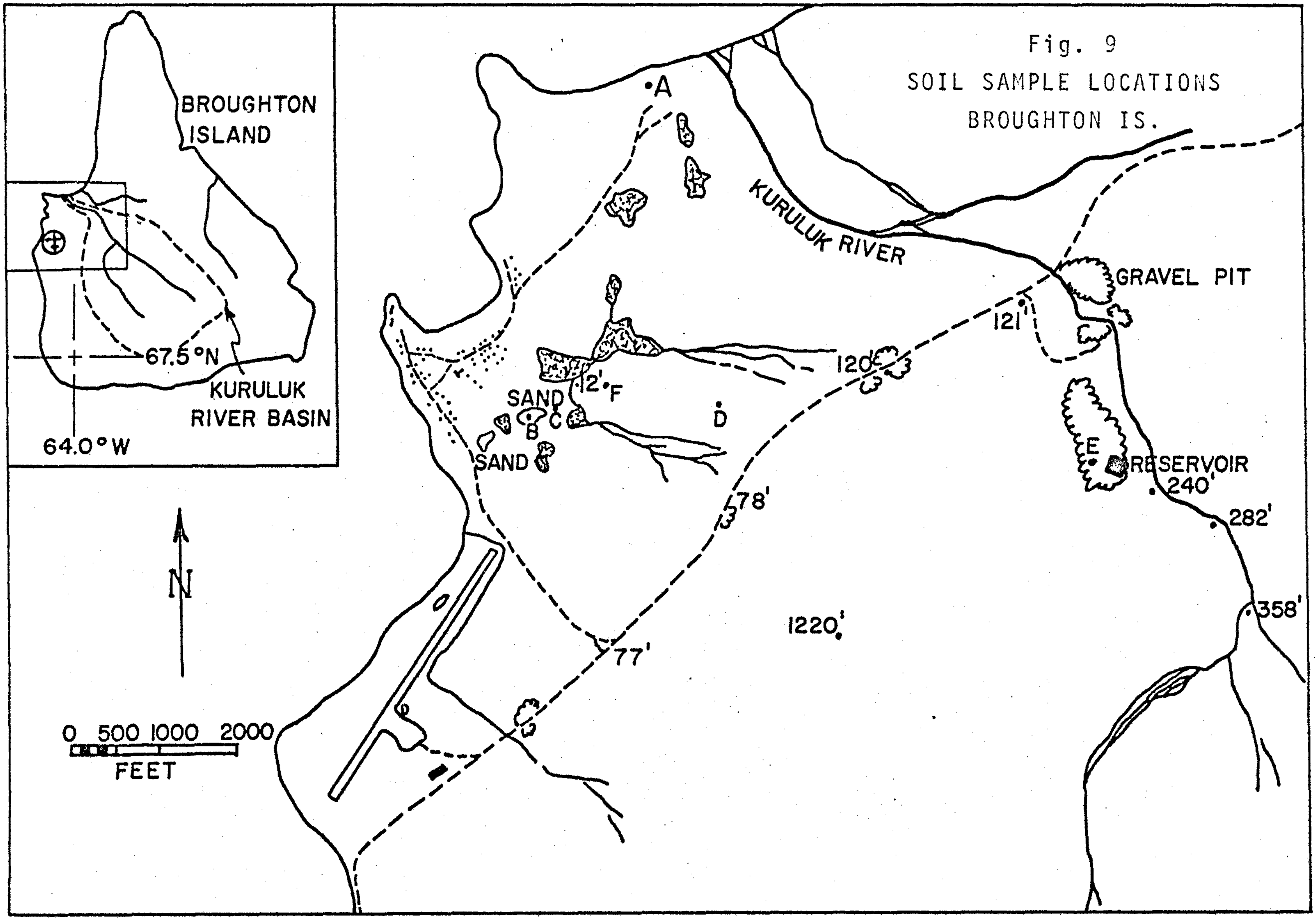


Fig. 9
SOIL SAMPLE LOCATIONS
BROUGHTON IS.

TABLE 11

Results of Soils Analysis

-Broughton Island-

Location (Fig.)	Description and Classification	Liquid Limit	Plastic Limit	Permeability
A	clean, white, uniformly graded, beach sand			$2.0X10^{-1}$ ft/min
B	uniform clean sand with increasing organic content with depth			$3.0X10^{-2}$ ft/min
C	uniform sand with some silt and gravel			$3.0X10^{-2}$ ft/min
D	inorganic silty, sandy clay with some stones in area with some boulders (30% clay content)	20%	14%	$1.0X10^{-5}$ ft/min
E	well graded sand with gravel and silt and contained permeable, uniformly graded, course sand lenses			$5.0X10^{-3}$ ft/min
F	sandy, clay silt 35% silt, 22% clay with gravel and some large boulders	17%	15%	$2.0X10^{-5}$ ft/min

available in small high arctic communities. In some cases, some or all of this machinery may be rented from nearby DEW line stations or private industries.

Typical equipment inventories are shown in appendices C and D along with typical rental rates.

3.7 Domestic Water Storage Tanks in Broughton

In Broughton, a survey was conducted of the various types of water storage tanks available within the buildings of the community. It was found that there was little standardization and that the types and capacities of the containers varied widely. Some 250 gallon, fiberglass tanks were discarded outside the houses because they were said to give a foul taste and odour to the water. Therefore most tanks in use were either plastic or galvanized steel and most were open at the top. Water was usually obtained simply by scooping it out manually. In the settlement office, a large 600 gallon tank was badly corroded and hot water from the electric heater was rusty brown, indicating the corrosiveness of the water.

Appendix D lists the various water storage capacities within the various buildings in the community of Broughton. It is assumed that Broughton is fairly typical of the small communities of the Arctic in this respect.

3.8 Comment on Electrical Generating Capacities of Small Communities

Electrical power in the arctic is very costly. For Pangnirtung the 1974 cost was 12¢ per K.W.H. and for Broughton the cost was 18¢ per K.W.H. The cost per killowatt-hour decreases as total consumption increases. For Frobisher Bay the cost is 7.7¢ per K.W.H. [39]. Since installations are small, there is usually at least 100% reserve generating capacity plus further reserve for future increases in demand. In Pangnirtung there are two 165 and two 300 KW diesel generators for a total capability of 930 KW. Peak demand for the 1973-1974 winter was expected to be about 350 KW [41].

In the diesel generation of power, a large percentage of the calorific energy of the fuel is wasted. This heat is presently being expelled to the atmosphere through the exhaust system of the generators. Approximately 4,000 BTU/KW/Hr can be recovered with the use of present heat exchange equipment [65]. That is, the amount of heat recoverable from waste heat is approximately equal to the amount produced as electrical energy. Such recovered heat has many possible applications. It may be used to heat large buildings, or to heat the water for distribution by pipeline or it might be used to reduce the ice cover on the water storage reservoir.

3.9 Interviews Conducted

During the field trip in the summer of 1974 a number of people living and working in the Arctic were consulted for their opinions and advice regarding topics which relate to water supply and sewage disposal. Some of these discussions or interviews are summarized here.

John Argue, Regional Supervisor for the Department of Local Government in Frobisher Bay, felt that the Inuits were very capable of adopting to more sophisticated technology and standards. However, he emphasized that they must believe something will work, or else it will not succeed. Therefore it is important to consult the local councils in arctic communities regarding any planned changes.

Consultation with doctors, nurses and some residents indicated that they felt disease within the communities of the Arctic was due as much to the lack of adequate supplies of water for washing as to the lack of adequate disinfection of that water.

Discussions and written communications with Bob Giroux, the settlement manager for Pangnirtung, and with Ian Creary, the settlement manager for Broughton, indicate that in both communities the excavated reservoirs are subject to losses from seepage and some sort of contamination which turns the water brackish. In Pangnirtung the drop in water level in the reservoir was at times less than that anticipated from the rates of consumption. Therefore it is assumed that there must be seepage into the reservoir from groundwater as the water level drops; this may be the source of the troublesome contamination.

Mr. John Fuller, the local superintendent for the Department of Local Government expressed the conviction that piped distribution systems should be buried as protection against vandalism and accidents.

4 MODEL DEVELOPMENT

4.1 Determining Flows in Rivers

The Arctic field work included the measurement of river stage and discharge in order to determine rating curves. This was done in order to convert records for the rivers under study to streamflows. In most cases, flows were low enough that a current meter could be hand-held to determine a depth-discharge relation. In rare cases where the water was too deep, flows were measured by using dye dilution methods or by use of inflatable rafts.

The current-metering of streamflow in this study was done by six different people, including the author and his supervisor. The resultant stage-discharge co-ordinates were used by the Water Survey Canada to determine rating curves which were in turn used to obtain discharge tables for the rivers. It was therefore necessary to develop an efficient method for obtaining accurate and consistent results from all the accumulated current meter data. To perform this task a program named GAGE was written, to both perform the calculations and list the results suitably.

GAGE divides the stream cross-section into trapezoids and multiplies their cross sectional areas by the average velocity to obtain flow. A summation of flows then yields the total discharge. A complete description, listing and example of GAGE can be found in appendix F.

4.2 Establishing the Rating Curve

In order to determine a valid rating curve for a given set of stage discharge co-ordinates, the method of least mean squares was used. A FORTRAN algorithm was adapted from a text of applied numerical methods [18], and then elaborated to form the basis of program CURFIT.

It is very common, and the policy of Water Survey of Canada, to plot the log of stage against the log of flows and then fit a first order (linear) regression to these points. Therefore CURFIT was coded such that it could easily perform a polynomial regression on the logs, as well as the original values, of stage and discharge. In this way, it was possible to check the shift in the rating curves from year to year, and to check our results against stage-discharge relations sent to us by the Water Survey of Canada.

CURFIT will produce polynomial regression equations of any specified order(s) from the lowest order, min, to the highest order, max in a single run and it will list the standard deviation in each case, and also plot the regression curve against the original data points or logs of the data points, in order that the user may choose an acceptable regression. A complete description, listing and example is given in appendix G.

4.3 Discharge Tables

For accurate and fast interpretation of the river stage records, and for the integration of those records, it is necessary to produce a standard stage-discharge table. For this purpose, program XLIST was written. XLIST uses the constants of the most suitable regression equation obtained from CURFIT to produce a stage-discharge table. A switching factor along with the appropriate functions, has been coded into the program so that the polynomial regression equation of the logs of the flow-discharge co-ordinates as well as the original data points might easily be tabulated. The coding has been written to be compatable with CURFIT. A complete description, and listing of XLIST may be found in appendix H.

4.4 Development of an Intermittent Supply Network

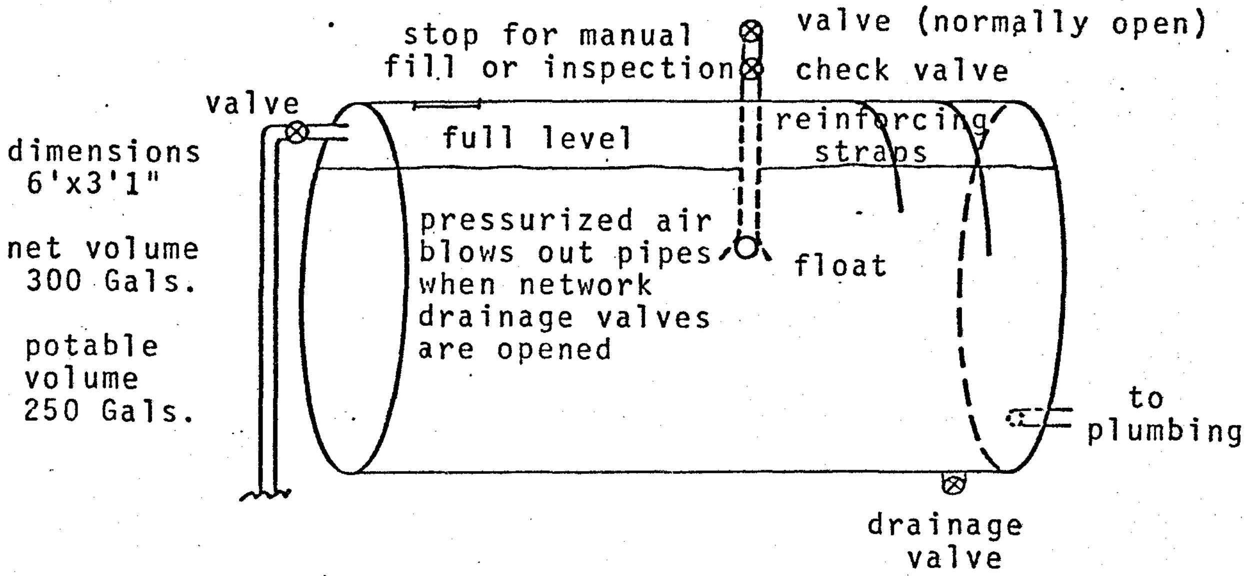
The need for improvements in water supply practice in the high Arctic has been demonstrated in previous chapters. It was also shown that sufficient quantities of good quality water are available in the summer months but that suitable methods for storage and delivery of this water must be found with appropriate consideration for costs, sociological effects and energy requirements.

Much time, money and effort have been spent on the design, construction and improvement of utilidors and re-circulating systems, but intermittent pumping has largely been neglected and its advantages overlooked. Although this method has been used in limited single main pipeline applications in some arctic communities and work camps, its full potential for supplying water to arctic dwellings on a year round basis has not yet been examined.

The proposed intermittent system basically comprises a pipe network laid on the ground or in a shallow bed of gravel, to supply a storage unit in each individual building. Such a network could be operated from a single pumping station and must be properly insulated and protected by a suitable exterior protective coat. Heat would be supplied, for example, by electrical heating elements placed between the pipe and the insulation. The pipe network would fill storage tanks, elevated within the houses, when the tanks were empty. Between supply pulses the pipes would remain drained and unheated. During the summer months, when temperatures are above freezing, the system could operate as a normal pressurized water supply network.

There are a large number of potential advantages with the proposed scheme over alternate methods. The water could be easily treated at the pumping station by a hypochlorinator and a simple fast filter, such as a micro-strainer, as other treatment is not likely to be required; many storage tanks already exist and could be modified to be compatible with the proposed pumping system and to provide a gravity feed to a simple plumbing system within the dwellings; such a network could be constructed in stages in order that the water trucks might be slowly converted to other uses and that the requirements of electrical power and operating skill might be gradually and effectively acquired; since the pipes are drained and unheated at least 80% of the time, there is little or no disturbance to the permafrost; since no return lines are needed and minimum velocities need not be maintained, much less pipe of smaller diameter may be used, resulting in large savings in energy and capital costs; the system may be integrated with heat exchangers to effect further savings in energy; the pipes may be carefully held at a uniform minimum temperature for further energy savings; heat loss from the pipes to the atmosphere occurs only 10% to 20% of the time and thus there is a great reduction of energy wasted; with (say) four days between supply pulses there is adequate time to repair any malfunctions; the pipes may be slightly buried to protect them from surface vehicle damage and vandalism and to prevent them from obstructing traffic or pedestriam movement; the pipe layouts would be relatively versatile and not require drastic reorganization of existing town plans in order to provide improved services; with the use of small diameter pipes, drainage can be aided by blowing air through the pipes; air, for blowing out the pipes, might be obtained from air pumps at the pumping station and/or by designing the storage tanks such that they contain a pressurized reserve of air which expands to force water out of the pipes when the network drainage valves are opened (Fig. 10).

Fig. 10 WATER STORAGE TANK



With 5 ATM.G. water pressure, air reserves which are 10% of the tank volume could collectively displace 5 times the volume of all the network pipes.

In designing the proposed intermittent network, there are a number of parameters which may be varied in attempting to minimize costs. These design parameters include:

a) the water demand

b) the size of the distributed storage tanks

c) pumping head

d) the rate or duration of pumping

e) pipe layout

f) pipe sizes

g) insulation thickness

h) capacity of the heating elements

i) the circuitry of the heat tracing system

j) the types of pipe, insulation and heat tracing tape used

The most difficult variable to determine is water demand. Water demand can be greatly reduced within the dwellings by supplying public facilities for laundering and showering, as is indeed being done at present in communities such as Pangnirtung. This also decreases the load on the sewage system and avoids the cost of individual showers, washing machines and dryers. However, even with such facilities, there is bound to be increased demand within the homes due to increased availability and changing housekeeping patterns [74]. If it is assumed that low quantity flush waste disposal can be achieved, and extravagant use be discouraged through water metering, then an initial design water demand of about 10 g.p.c.d. may be reasonable. Larger users could supply proportionately larger storage tanks and also pay the extra cost of the water and sewage disposal. Storage capacity within each dwelling could be balanced so that most of the distributed storage would be low at the same time.

In order to determine at the outset, the sensitivity of the total system cost to each of this large number of variables, a simple program was written for operation in time sharing mode. This model reduced the supply system into one length of pipe supplying a single node throughout a typical arctic winter. Repeated runs of the program indicated that the maximum practical pumping head gave the lowest costs, since it reduced the duration of pumping. It showed that the storage capacity within the dwellings should be at least 50 gallons per capita, and that about one inch of calcium silicate insulation or equivalent was required on a typical two inch supply line. It also indicated that power loadings and costs were well within practical limits and probably less costly than any other system heretofore advanced.

With these results it was possible to continue to investigate the optimal design and costs associated with actual pipe networks. It is assumed that the maximum practical pumping head is used and that the average size of water storage tank is 250 gallons, since the average occupancy of native arctic dwellings is approximately five [41].

4.5 Optimal Design of the Pipe Network

The layout of a pipe network is dependent on the local topography and the town plan for each community. It will also be greatly influenced by traffic patterns and the location of the main storage reservoir. Therefore, to analyse the flows within a pipe network, a Hardy Cross analysis was programmed and design charts for estimating the friction factors and approximate flows within small diameter pipes were prepared (appendix K). Optimization of the pipe network may then proceed by a trial and error approach. The Hardy Cross network analysis (program HCNA) is described and listed together with a worked example in appendix I. The program starts with assumed flows and then alters these to balance head losses. It then lists each pipe giving the total head loss and flow and the energy gradient for that pipe. The design charts of appendix K will aid determination of initial pipe sizes and flows and will also aid determination of flows in dead-ended pipes.

The procedure, then, may be summarized as follows: First assume a duration of pumping, say 5.0 hours. This will determine the flow rate since all distributed storage must be filled within this period. Then determine the supply links so that the total length of pipe is minimal and so that drainage may be accomplished at a minimum number of convenient points. Next, pipe diameters are selected such that the total cost of the pipe is minimal. This may be done in a more exact manner by first running program SYSOPT, which is described in the following section, for one foot of each diameter of pipe and plotting the total annual cost vs. diameter. Then use this function to determine the optimal pipe diameters. A few trials will normally indicate the optimal layout and diameters of the pipe network, because of the topographic and traffic constraints.

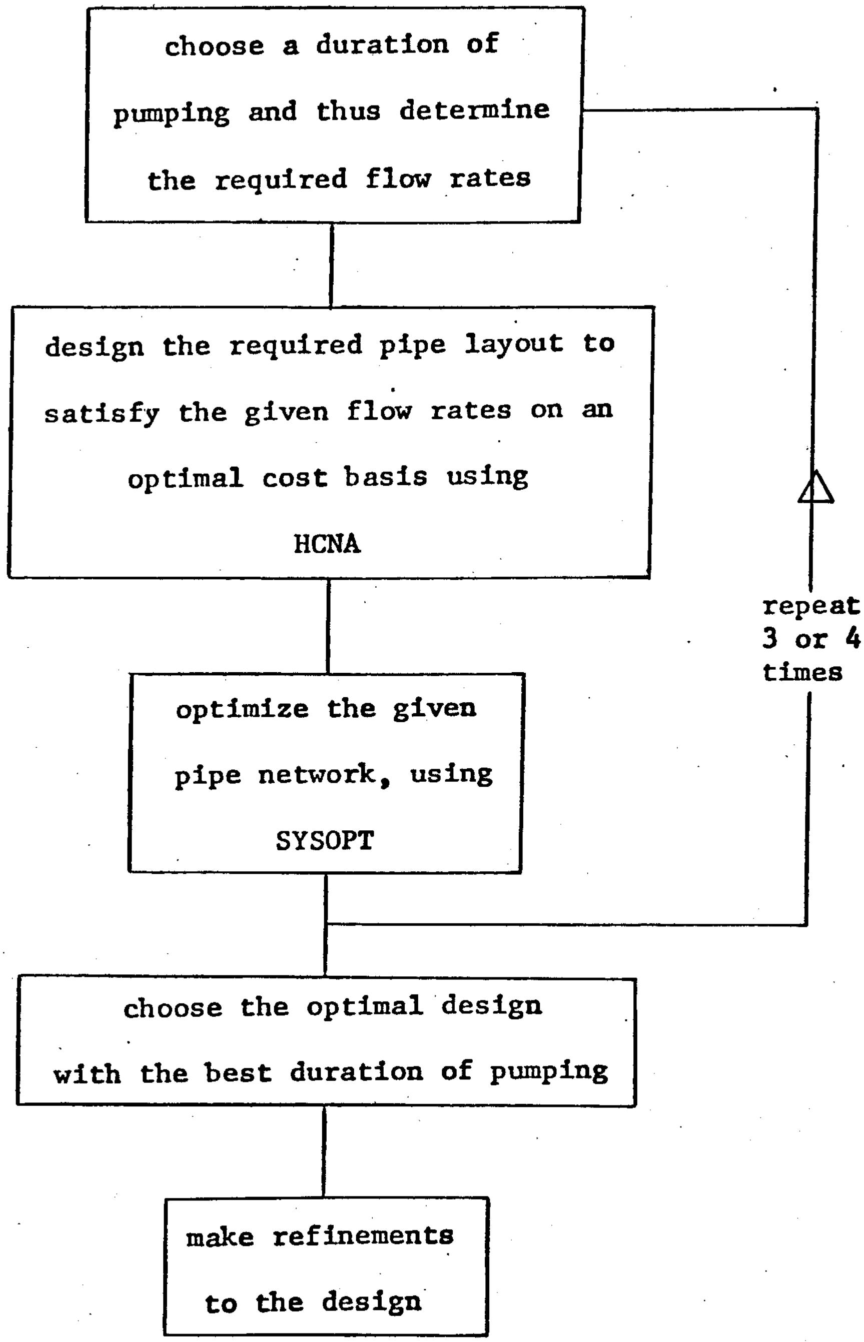
In order to optimize the duration of pumping it is necessary to repeat the procedure, in other words to determine an optimal network for several different durations of pumping. These results are used to find the global optimum. The entire procedure is shown in flowchart form in Fig. 11.

The optimization of a network for the requirements of heat tracing tape, insulation and power is discussed in the following section.

4.6 Optimal Design of Power and Insulation Requirements

Once the pipe networks for various durations of pumping have been determined, a number of parameters may be altered in attempting to minimize costs. Higher capacities of heat tracing tape allow the system to be brought up more quickly to operating temperature and thus heat is lost for a shorter period of time. However, heat tracing tape is costly and therefore a balance must be determined. Furthermore, the insulation also plays an important and complex role. Larger amounts of insulation require larger amounts of sensible heat to bring them up to operating temperature and incur increased wrapping and placement costs. However increased insulation thickness

FIG.11 FLOW CHART OF DESIGN PROCEDURE



also greatly reduces heat losses during operation. Therefore insulation thickness must also be carefully selected. If the circuitry is to be simple, and requires that the entire network be activated at once, then both the insulation and power of the heat tracing tapes must be chosen so that the whole network will reach operating temperature within the optimal warm-up time for the minimum cost. In addition, the properties of the insulation material, the pipe material, and the exposure to the wind affect both the amount of energy required for warm-up as well as the rate of heat loss. Finally, the circuitry itself can be installed in a very wide variety of designs. Increased complexity in circuitry can help attain increased simplicity of operation and savings in power costs, but such circuitry itself is costly, in design, maintenance and construction. This latter consideration cannot properly be programmed. However, we could examine possible cost savings in terms of heating costs.

The program written by the author which performs the above tasks is named SYSOPT. It determines the design having the minimum annual cost for power, pipe, heat tracing tape and insulation. All cost functions are written into subroutines with all data being transferred through an unlabelled common block. Thus the subroutines may be easily altered to include estimates of other costs such as fittings, wrapping and installation. Costs of materials may be computed from arrays of cost data as supplied by manufacturers, or empirical cost formulas may be added to the subroutines. Thermal properties are calculated from heat transfer equations so that the effect of using various alternative materials may be easily ascertained.

The equations used are:

$$RHL = \frac{TD \times AO \times COND \times FACT3}{XINS \times 3.41}$$

where:

RHL is the rate of heat loss in watts per foot per hour.

TD is the temperature difference in degrees fahrenheit.

COND is the thermal conductivity in British Thermal units per square foot per degree fahrenheit per hour per inch.

FACT3 is a wind factor which is 1.00 if the pipe is protected from the wind. The default value used is 1.12 for pipe exposed to wind. The value of 1.12 is for a wind velocity of 20 miles per hour. Other values may be obtained from most handbooks of heating, refrigeration or cold weather pumping [2, 3].

XINS is the insulation thickness in inches.

The factor 3.41 converts heat losses to units of watts per hour.

AO is the log mean area of the insulation surface per foot length of pipe in square feet, determined from:

$$AO = \frac{\pi/12\ (D2 - D1)}{LOG_{10}\ (\pi/12 \times D2/D1)}$$

where:

D1 is the outside pipe diameter in inches and,

D2 is the diameter to the outside of the insulation in inches (e.g. the outside pipe diameter plus twice the insulation thickness).

A flow diagram of the coding in SYSOPT is shown in Fig. 12 . A linear programming procėdure is used in which all combinations of design parameters are tested and the location of those giving the least cost solution are stored. Tests are performed for physical constraints and penalty costs assigned where constraints are violated.

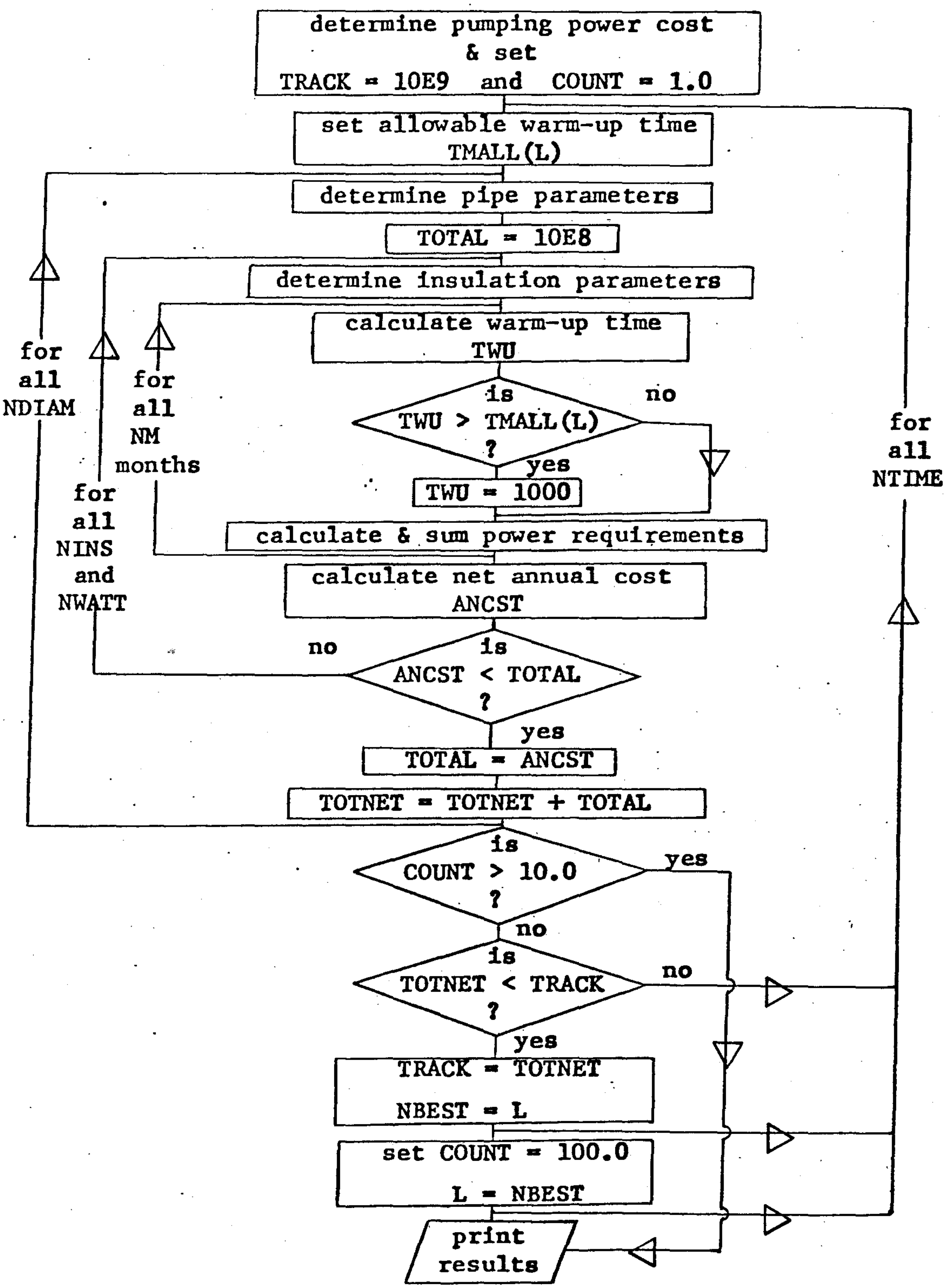
Brief descriptions of the input variables are given in the comment cards at the beginning of the program listing. Variables are listed in the same order in which they are read into SYSOPT. The required format is also given. A large number of variables have been incorporated in order to make the program flexible.

DENINS, the density of the insulation, and SPHI, the specific heat of the insulation have been included so that a cost-benefit determination for various types of insulation might easily be made.

WPER is the length of the winter period and is used to estimate the total number of pulses. It does not have to coincide with the number of days in the winter months that are chosen.

TOPER is the operating temperature of the network. A safety factor may be included here. A temperature of $40^{o}F$ was used by the author to allow a margin of 8^{o} above freezing. Temperatures lower than $40^{o}F$ should not be used

FIG. 12 PROGRAM SYSOPT FLOW CHART



and it may be desirable to use design temperatures as high as 45^{o}F.

Four design factors are included in the input. FACT1 is the average percentage of the cross sectional area of the pipes which retains water rather than air after drainage. This water will freeze during the drained period. The program calculates the energy required to heat and melt this ice, and bring the temperature up to operating level. A reasonable estimate of the amount of water retained might be 10%. A considerable amount of energy is required to melt this ice and therefore adequate drainage of the pipes is very important. The use of air ejection is advisable.

FACT2 is the average percentage of water consumed at the time of supply. Some users will deplete more of their storage than others during the interval between supply. An estimate of 80% consumption may be reasonable as a first guess. The accuracy of this factor can be improved through field operations.

FACT3 is a wind factor used in heat loss calculations, ranging from 1.00 to 1.20 for insulated pipe.

FACT4 is set to zero or one depending on the type of circuitry considered. If it is zero then each diameter of pipe is considered to be on a separate circuit. In such an operation, the largest pipes requiring longer warm-up times would be activated first, then the next largest and so on. This can be timed so that all pipes reach operating temperature at approximately the same time. In this case, an optimum warm-up time is not required and therefore only one large "dummy value" for allowable warm-up time (greater than 10 hours) needs to be entered into the array of allowable warm-up times. If FACT4 is 1.0, then it is assumed that all pipes begin warm-up at approximately the same time. In this case, the program searches for the combination of warm-up time, insulation thicknesses and tracing tape capacities that will yield an overall optimal solution. The procedure is as follows: For each allowable warm-up time being tested, the program will search for the combination of insulation thickness and tracing tape capacity which most economically yields a warm-up time that is less than or equal to the allowable warm-up time. This is done for each diameter of pipe. Where a warm-up time for a certain pipe is less than the allowable warm-up time (which often occurs) the program uses the difference and calculates the cost of that wasted energy. The warm-up time and parameter values which incur the least total annual cost are listed as optimal.

TDRAIN is the time required to drain the system and was estimated at 1.5 hours by the author.

The last data entered are NMON, the number of winter months (those months with average temperatures below freezing) and TARRAY(NMON), the array of monthly ambient temperatures. The average monthly temperatures should give a good estimate of the average heat losses. However, it is advisable to enter the minimum monthly temperature for the coldest month in order that the system be capable of operating under severe conditions.

All data reading operations are performed by a subroutine called SYSIN. This subroutine should be checked when entering data, since it also contains statements for reading arrays of pipe and insulation costs.

All various sets of operations are performed in separate subroutines. These subroutines and the functions they perform are listed in the comment cards of program SYSOPT in appendix J. This division of operations makes it simple to change or elaborate the program.

SYSOPT was checked for both logical and arithmetic accuracy and found to give valid results. The validation, as well as a complete description, and listing may be found in appendix J. Applications of the methods are given in the following chapter.

4.7 Other Design Considerations

Supplying water by the method proposed in section 4.4 requires that adequate water be available. This method does not directly solve the problems of sewage disposal. Water storage, water supply and sewerage, as well as power supply are all related problems in the

Arctic and the overall optimal solution would generally be an integrated system. Section 2.5 attempts to show that open reservoirs are probably the best method for storing water and section 3.8 discusses the amount of energy wasted to the atmosphere by the diesel-electric generators in arctic communities. The proposed water supply system would require additional generation of power and lead to increased heat waste. It seems quite obvious that this waste heat should be utilized. Probably the most simple application is to locate the generators adjacent to the pumphouse and the reservoir. The waste heat could then be used to increase the reservoir water temperature by using it as cooling water and/or, more importantly, by using a heat exchanger and water pump to capture the heat from the exhaust fumes. Waste heat might also be used to warm the pumphouse. The benefits of warming the reservoir water are: (a) that it would keep the water well aerated and thus improve its quality, and, (b) by reducing the ice cover, there would be much less stress on the reservoir liner and (c) a reservoir of given capacity would yield a greater quantity of potable water.

The most simple and economic solution to the sewage disposal problem appears to be the use of large holding tanks and low quantity flush toilets within the houses, to be pumped out by service trucks from outside the house. The trucks could then transfer and pump the sewage into a lagoon which would provide adequate treatment during the summer months and be flushed in September. Total haulage would be less than is presently the case for water supply. The existing water trucks could be readily converted to this use. The sewage holding tanks might also eventually be connected to a vacuum sewer system, or incorporated in a similar way to an intermittent system of sewer pipes.

Ideally, for each community there should be a carefully designed long-term plan for the development of simple, effective and flexible integrated services. In each case the overall cost should be minimized. It should be determined whether it is more economical to pump directly from a distant reservoir or whether secondary storage within the community is preferred. For some large users, it may prove more economical to provide a continuous supply, rather than a pulsed supply.

The cost of an excavated reservoir could also be very much reduced by computer optimization. The bottom dimensions and excavation depth should be carefully chosen, since excavation in permafrost and soil with large boulders is difficult, and it may be more economical to simply construct banks from external fill material.

The above proposals would greatly improve the health and aesthetic quality of arctic communities, and would provide high levels of service, employment and self reliance without introducing impractical complexity or capital requirements.

5 MODEL APPLICATIONS

5.1 Determining the Flow of the Duval River

Seven stream gaugings of the Duval River were performed during the 1974 field season. The flows estimated by these gaugings, as analysed by GAGE, ranged from 72 to 850 CFS. Regression analysis of the stage-discharge points by CUR-FIT indicated that a first order log-log equation best described the stage-discharge relationship:

$$\text{Flow} = 10.0^{(1.481295 + 3.332762 \text{ LOG}_{10} \text{ STAGE})}$$

Using this relationship to integrate the entire stream gauge record, it was determined that the net discharge of the Duval River for 1974 was approximately 923 million cubic feet, within the period of record.

5.2 The Design of an Optimal Intermittent Pumping Network For Pangnirtung

A network of pipes was designed for Pangnirtung in such a way that it would pass close to all the buildings requiring water in the hamlet and make the minimum number of road crossings. Furthermore it was designed to facilitate drainage and be easily expanded. Design was performed for a ten year population projection, even though the design life of the system is considered to be fifteen years or more. This was done to avoid oversizing the pipes.

By designing for this intermediate population projection, the length of the pumping interval can be altered to compensate for future growth and thus the net cost over the life of the system is kept to a minimum.

In performing the design, Pangnirtung was divided into two parts, Upper Pangnirtung and Lower Pangnirtung. Lower Pangnirtung lies northwest of the airstrip and Upper Pangnirtung lies southeast of the airstrip. The two water distribution networks are connected by a 2.50 inch pipeline passing the eastern end of the runway. Each home is assumed to have a 250 gallon storage tank. It is also assumed that each family has five members and that they collectively consume 50 gallons per day within their home. For an 80% consumption, the duration between supply pulses is four days. The consumption rate in the school is assumed to be 10 gallons per student per day for a 10 year projected enrollment of 350 students. Therefore the system is designed to supply 14,000 gallons per pulse to the school. New laundry facilities and showers are not accounted for. It is assumed that these will be located close enough to the pumphouse to be supplied independently. Extra demands from buildings such as present laundry facilities, the nursing station and the hotel are taken into account. Figures 13a & 13b show the distribution of water demand and the pipes used to supply this demand.

With 3000 feet of quarter inch pipe allowed for ser-

Fig. 13a DISTRIBUTION OF PIPES AND WATER DEMAND IN UPPER PANGNIRTUNG

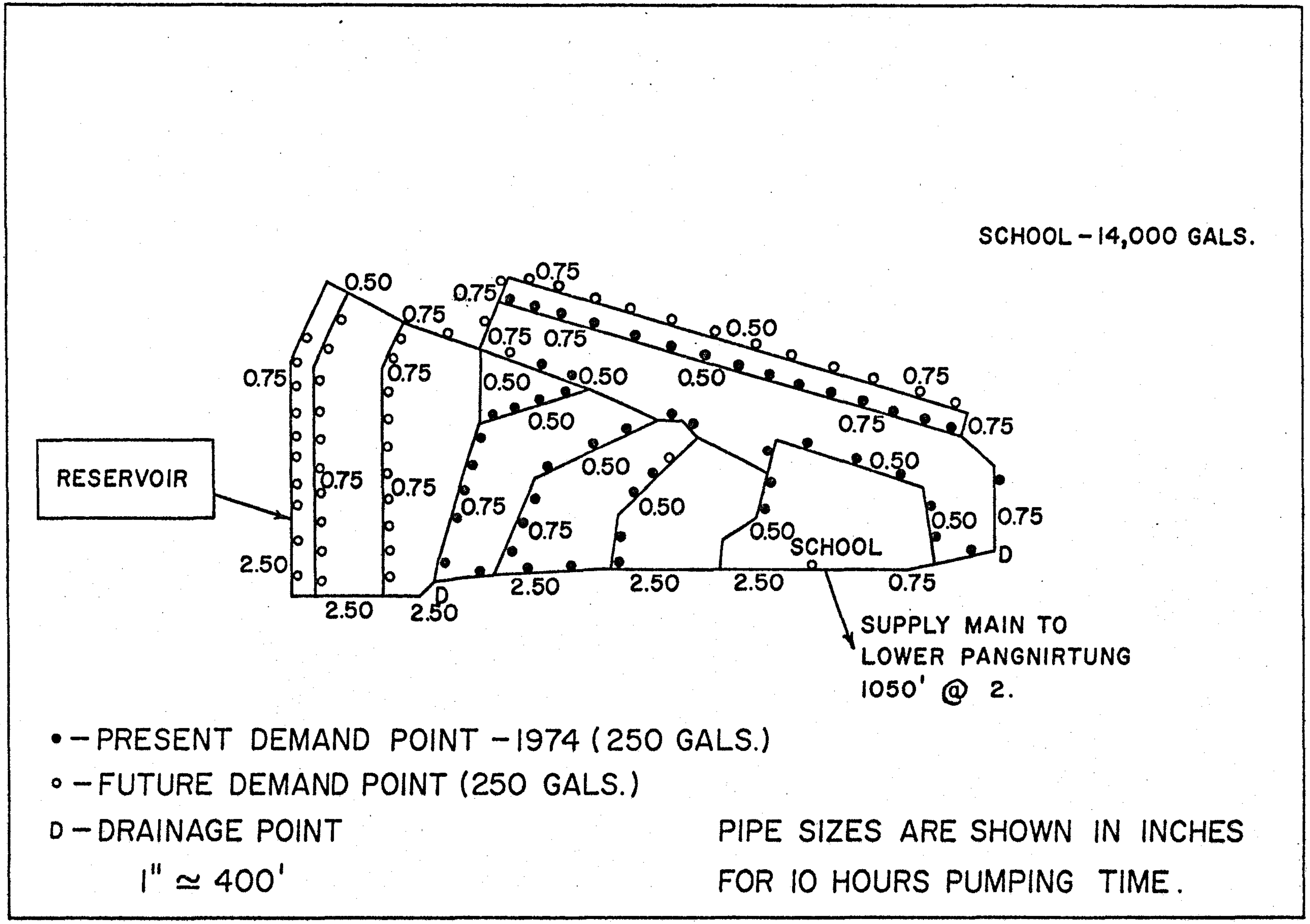
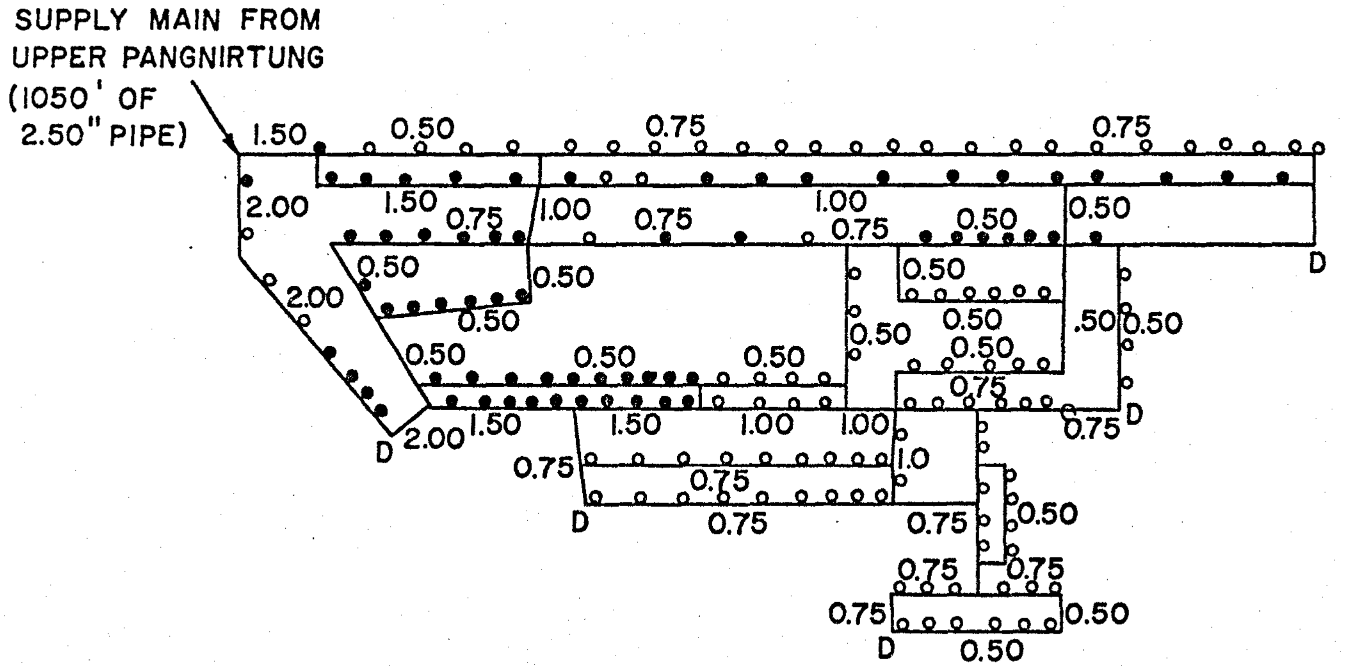


Fig. 13b DISTRIBUTION OF PIPES AND WATER DEMAND IN LOWER PANGNIRTUNG



• – PRESENT DEMAND POINT (1974)

∘ – FUTURE DEMAND POINT

D – DRAINAGE POINT

1" ≃ 400"

PIPE SIZES ARE SHOWN IN INCHES FOR 10 HOURS PUMPING TIME.

vice connections (large users would employ larger connections) the total length of pipe required was 21,000 feet, or approximately four miles of pipe. Network analysis using HCNA were performed for pumping intervals of 5, 10, 15 and 20 hours. The net annual costs were then determined from SYSOPT and net annual cost plotted against the duration of pumping. It was found that the optimal balance of power consumption and capital costs occurred at about 10 hours pumping time. The design load capacities for the heat tracing tape ranged from two to five watts, and heat-up times ranged from 40 minutes to five hours for the various pipes within the network. The total annual cost of power, insulation, pipe and heat tracing tape for fifteen years at ten percent interest was found to be about $15,641. The largest pipe required at this pumping interval was 2.5 inches in diameter with most of the pipe in the network being in the 0.50 to 1.00 inch range. Insulation thicknesses (polyurethane) were found to be optimal at 0.50 inches for the smaller pipes and 0.875 inches for the 2.50 inch pipe. Therefore the maximum net diameter is less than 4.50 inches.

Table 12 presents the pipe requirements for the various pumping durations. Table 13 and figure 14 illustrate the relationship between net annual cost and pumping duration.

TABLE 12

ESTIMATED PIPE REQUIREMENTS FOR PANGNIRTUNG
(FEET)

TIME (HRS.)	PIPE SIZES (INCHES)								
	0.25	0.50	0.75	1.00	1.50	2.00	2.50	3.00	3.50
5.0	3,000	5,393	3,233	2,079	3,100	490	1,120	1,900	685
10.0	3,000	7,368	4,302	1,940	1,025	780	2,585	-	-
15.0	3 000	8,426	3,934	950	1,605	2,550	535	-	-
20.0	3,000	10,240	3,020	1,035	1,120	2,585	-	-	-

TABLE 13

OPTIMAL NETWORK ANALYSIS FOR PANGNIRTUNG

Time (Hrs.)	Pumping Horsepower	Maximum Power Load (KW)	Capital Cost	Annual Cost of Capital	Annual Cost of Power	Total Annual Cost
5.0	11.7	84.7	91,093	11,636	4,744	16,381
10.0	5.9	58.7	83,881	10,715	4,925	15,641
15.0	2.9	53.3	79,896	10,206	5,927	16,133
20.0	2.1	50.5	77,108	9,850	6,927	16,778

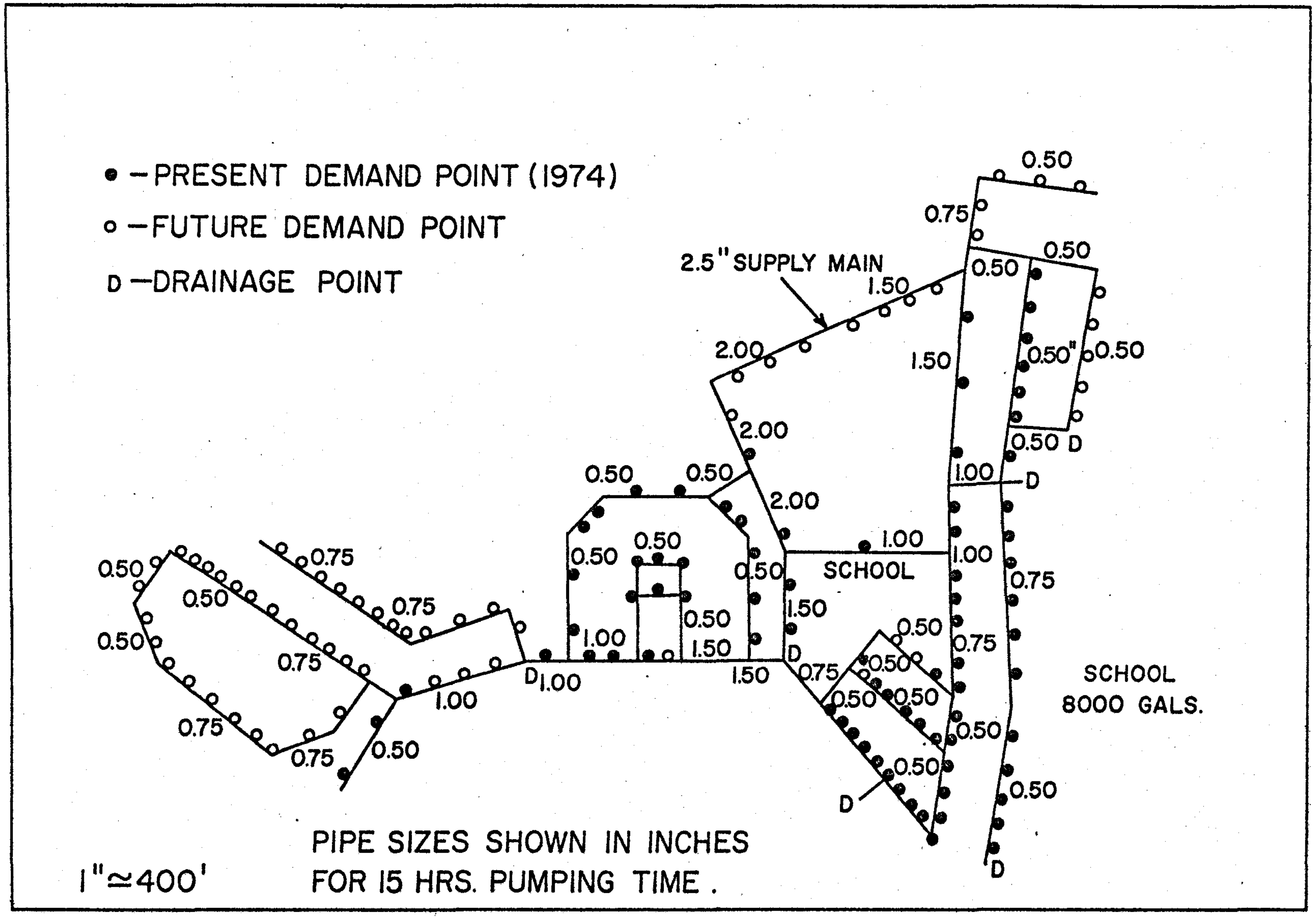
5.3 The Design of an Optimal Intermittent Pumping Network For Broughton

The average temperatures on Broughton Island were estimated to be about 9°F colder than in Pangnirtung and the cost of power used was 18¢ per kilowatt hour compared to a cost of 12¢ per kilowatt hour for Pangnirtung. As in the Pangnirtung application, the minimum monthly temperature rather than the average monthly temperature was used for the coldest month. This ensures adequate heat tracing capacity and insulation thickness in order to handle the most severe conditions likely to be encountered. It was assumed for Broughton that an adequate reservoir could be constructed about half an mile from the edge of the settlement. Such a reservoir could be located in the clay deposits northeast of the settlement, to be filled by a gravity feed from the reservoir in summer. This location is estimated to be about forty feet above the elevation of the point where the supply main would feed into the supply network.

The distribution network was designed in a manner similar to Pangnirtung. The 10 year projected enrollment at the school is 200 students for a water demand of 8,000 gallons. A few pipes were oversized in order to facilitate drainage (Fig. 14).

The resulting net annual cost was found to be higher than that for Pangnirtung due to the long reservoir con-

Fig. 14 DISTRIBUTION OF PIPES AND WATER DEMAND IN THE SETTLEMENT OF BROUGHTON



nection and the high cost of power.

The optimal pumping interval (Fig. 15) is approximately 14 hours, which is the shortest duration at which a 2.5 inch connection to the reservoir is feasible. There are approximately 67 pulses in one winter period. The 2.5 inch line requires 1.25 inches of polyurethane insulation and a five hour warm-up period. Reduced power costs would greatly reduce the system costs.

Table 14 lists the pipe requirements for various pumping durations and table 15 lists some of the design parameters and costs of the optimal network.

TABLE 14

ESTIMATED PIPE REQUIREMENTS FOR BROUGHTON
(FEET)

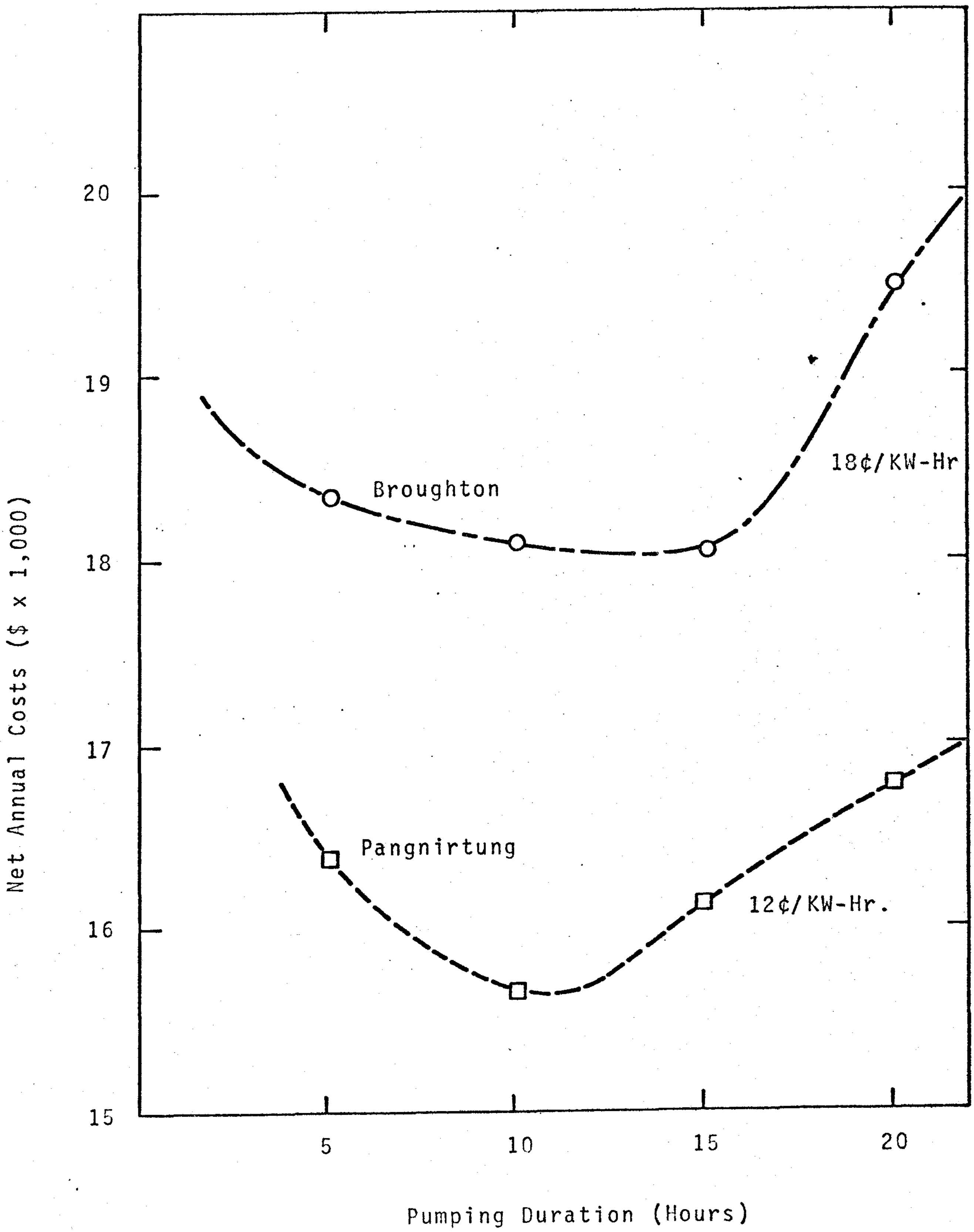
TIME (HRS.)	PIPE SIZES (INCHES)								
	0.25	0.50	0.75	1.00	1.50	2.00	2.50	3.00	3.50
5.0	1,000	2,540	3,270	1,620	2,530	1,235	1,480	-	2,650
10.0	1,000	5,930	1,240	2,410	1,615	1,480	-	2,650	-
15.0	1,000	6,780	2,560	845	1,670	820	2,650	-	-
20.0	1,000	8,250	1,190	1,175	2,060	-	2,650	-	-

TABLE 15

OPTIMAL NETWORK ANALYSIS FOR BROUGHTON

Time (Hrs.)	Pumping Horsepower	Maximum Power Load (KW)	Capital Cost	Annual Cost of Capital	Annual Cost of Power	Total Annual Cost
5.0	6.0	70.0	85,108	10,872	7,481	18,353
10.0	3.0	52.7	78,416	10,017	8,095	18,112
15.0	2.0	45.4	71,848	9,178	8,851	18,029
20.0	1.5	43.8	70,307	8,981	10,487	19,468

Fig. 15 NET ANNUAL COSTS AS A FUNCTION OF PUMPING DURATION



6 DISCUSSION

6.1 Water Quality and Quanitiy

Field tests performed in this study showed that the raw water supplies used on Broughton Island and in Pangnirtung might at times contain total coliform concentrations which are higher than the maxima recommended by government agencies. However the fecal coliform counts were always zero and the water appears to be of a quality which is safe for drinking.

The biological quality of the water samples collected from homes was often much poorer and unsafe for drinking. High counts of fecal coliform as well as total coliform were recorded. Apparently, water is being contaminated during and after delivery. Furthermore, water, with the particular chemical qualities which are normally exhibited by surface waters of the eastern high Arctic when stored in large containers within relatively warm houses, is an excellent medium for bacteriological growth.

The problem is twofold: (a) there is very little awareness by the inhabitants of the North of the relationship between health and water quality and (b) no suitable methods of controlled sterilization and protection of the water supplies are provided in most small high arctic communities.

Suitable treatment of raw surface waters is relatively simple in most locations, as only some filtering and chlorination are required and perhaps some batch treatment of the water in the reservoir for corrosiveness. The use of pipes, rather than trucks, and closed storage tanks, rather than open containers, would greatly facilitate proper, controlled treatment.

Increased quantities of water are also required, especially throughout the winter months. Quantities adequate for cooking, washing and cleaning will require an increase to a minimum of 10 g.p.c.d from the present 2 g.p.c.d. in conjunction with improved methods of sewage disposal. The use of low discharge flush toilets, and public laundry and shower facilities, will help reduce distribution costs and facilitate the conservation of water supplies.

6.2 Water Storage

Quantities of water large enough to provide at least 10 g.p.c.d. plus adequate supplies for schools, laundries and shower facilities throughout an eight or nine month winter period need to be provided for most of the small communities in the high Arctic. The method employed should safeguard water quality and must also be economically feasible. It appears, from the analysis of section 2.5 and by examination of present successes in the use of sewage lagoons that excavated and lined reservoirs will provide a least cost solution in most locations. This method minimizes operating costs and provides labour for local inhabitants. The use of computer optimization techniques can provide large savings in construction and operation costs. The use of berms rather than deep excavations will help to avoid problems of excavation in rocky permanently frozen ground and to reduce the problems of hydrostatic uplift on reservoir liners.

6.3 Water Supply

The cost and the design parameters obtained in section five suggest that an intermittent water supply system is a workable and economical solution to water supply problems in the far north. A surprising result of the analysis of pulsed water supply to distributed storage is the small size of the pipes required. In a ten hour supply period, 0.25 inch pipe can supply over 600 gallons of water where a gradient of 2 Ft./Ft. is available. Therefore 0.25 inch pipe is adequate for domestic service connections. For an energy gradient of 0.1 Ft./Ft., a 0.50 inch pipe can supply 750 gallons in 10 hours or enough water for 3 homes. Although flow rates may be low, the constant flow time of 10 hours makes it possible to supply enough water for 4 or 5 days with very small pipes. Since pipes are heated only about 10% to 20% of the total time, they require relatively thin insulation and will not seriously disturb the permafrost. Since total diameter (pipe plus insulation) are kept small, the network becomes relatively simple to construct and maintain.

It is proposed that the pipes could be pre-traced with electrical heating cables and pre-insulated, and have a tough waterproof protective coat applied in a factory so that only simple connections need to be made within the field. It may also be possible to simplify the supply networks, using small standard modules which might easily be replaced if trouble should occur. Thus a network could be easily constructed, expanded and maintained by local labour, and with local equipment.

Appropriate changes could easily be incorporated into SYSOPT so that optimal designs can be obtained using these standardized modules.

Firefighting should be handled by a volunteer force using a tracked vehicle and dry chemical extinguishers as is presently being done in Pangnirtung. This is not only adequate, but preferable, since buildings in the small communities are small and highly flammable, and because the use of fire hydrants, on any type of piped distribution, is both physically and economically impractical. Fire hydrants require careful protection against freezing and the design of distribution systems for fireflow requires much larger pipes. The installation of fire hydrants on a pulsed system would not be feasible since long warm-up times are required.

An accurate cost comparison of the intermittent system with alternative methods is difficult to make due to the variations in levels of service and quantities of water and sewage transported. However an approximate cost comparison is nevertheless valuable at this point. It is proposed here that each family in Pangnirtung be allowed approximately 50 gallons per day for home consumption, and each student be allowed an additional 10 gallons per day and that low flush toilets and public showers and laundry facilities be provided. If it is assumed that a 15 year projection is used, then we are designing for 250 families and using a capital recovery factor of .11746 (at 10% interest). It is also assumed that water and sewage tanks can be installed for about $400 each and that a water and a sewage reservoir can be constructed for the cost determined in section 2.5. It is also assumed that sewage pumpout costs would be similar to water delivery costs as reported by the consultants [38, pg. 19], inflated to 1975 costs. Two trucks would be required. Therefore costs are as follows:

<u>Capital Costs</u>

Pipe network	83,881
Control Equipment	20,000
Construction	100,000
Treatment Plant	300,000
Water tanks (250 x $400)	100,000
Sewage tanks (250 x $400)	100,000

Water Reservoir	456,300
Sewage lagoon	456,300
Laundry & Showers	700,000
School (sewage & water tanks)	15,000
	2,331,481

Annual Costs

Water Supply operation	13,000
Maintenance & supplies	5,000
Sewage Pumpout	94,141
Power	4,925
	117,066

Therefore, total annual cost is approximately:

(2,331,481 x .11746) + 117,066 = $390,922/year

This is about $1,560 per family per year. This cost may be greatly reduced if reduced costs for the reservoirs and the laundry and shower facilities are achieved.

The consultants [38] obtained costs of $3,868,000 for water and sewage networks. This is exclusive of the cost of a reservoir, sewage treatment, water treatment or any public facilities. It also does not include operational costs. Their costs may be estimated as follows:

Network costs	3,868,000
Reservoir costs (40 g.p.c.d.)	1,000,000
Plumbing requirements	750,000
Sewage treatment	500,000

Water treatment	100,000
	$6,218,000
Annual Costs	60,000

Total annual costs amount to $790,366. This is more than double our costs, which include necessary public facilities.

6.4 The Role of the Inuit

The design of any water distribution and sewage disposal system for small communities of the far north must take account of the fact that skilled labour is lacking. It should also take into account the conditions that exist in housing, traffic, local Inuit and white society, and the problems in health and hygiene that are faced.

On the above counts, it is found that an intermittently pumped water supply system and sewage disposal into a treatment lagoon would be best. It could be largely constructed and operated by local labour, construction could be easily done in stages in order that experience and skills might be acquired by the Inuit, and apart from the electrical components, the entire system would be simple to construct or repair. Permanent employment would be created for a number of operators and the transition from trucked supply to piped supply would be done gradually and cautiously following present habits. Specially constructed or adapted water storage tanks would be required in order to make the intermittent system operable but other than that, alterations to the plumbing within the homes could be left to the discretion of the inhabitants or those who rent the houses. The storage tanks could operate on an automatic demand pump or they could be elevated to employ a gravity feed.

Sewage disposal would operate independently of water supply for greater simplicity of operation and maintenace. A sewage lagoon could be constructed, after which time the transition from honeybags to low discharge flush toilets and holding tanks could be undertaken. This system would be simple to construct and operate with local labour, and it could employ the drivers and trucks that presently deliver water. Sewage holding tanks might later be converted to vacuum sewage disposal or a similar type of intermittent system.

The pipeline could be covered with gravel, at or near grade, in most locations and it could cross all roads through small diameter pipe culverts. Therefore the new system would not be unsightly or disrupt present traffic patterns. Furthermore, it would be protected against vandalism.

Due to the differences in habits, the water demand among the white population will probably remain higher than that among the Inuit population for a number of years. With the intermittent system, the sizes of the water tanks can be varied to match demand and people could be taxed according to the size of tank that they used in order to avoid expensive and complicated metering.

Finally, the people should be educated in hygiene and preventative medicine in order to help safeguard the quality of the water supplies and ensure its proper use.

6.5 Recommendations for Further Work

The next logical stage in this work would be to construct in the field, a reservoir and pumphouse and to connect ten or twenty homes. With such a system it would be possible to investigate alternate designs for pipe placement in order to allow for thermal expansions and contractions. The pipe may simply be placed in a gravel berm, or inside a larger culvert pipe and then slightly buried or perhaps it might be placed under covered half sections of discarded oil drums which abound in the Arctic. In some locations the pipe may have to be slightly elevated to pass over low wet areas, and many different designs would need to be considered. Thermal expansion and contraction can be handled by a number of methods. The pipe can be bent and placed in a sin wave pattern or it may be placed in a zig-zag pattern, or it may contain expansion loops or expansion joints. Automatic water treatment methods and electrical operation need to be tested. All components should be tested under cold weather conditions and closely monitored for at least one winter period. Such a trial operation might be attempted in Pangnirtung and/or Broughton.

The work of this thesis could also be extended. The computer programs listed could be made interactive and other programs to optimize reservoir design and operation would also be very beneficial.

It is hoped that the work in this thesis may initiate improved solutions and attitudes for the problems of engineering in the high Arctic.

BIBLIOGRAPHY

1 Alter A. J., (1975), "The Polar Palace", Northern Engineer, Vol 5, No. 2, pp 4-11.

2 Alter A. J., (1969), "Water Supply in Cold Regions", CRREL Pubication, III-C5a, January.

3 Alter A. J., (1969), "Sewerage and Sewage Disposal in Cold Regions", CRREL Publication III-C5b, January.

4 Alter A. J., (1957), "A Guide to Arctic Water Works Thermology", Consulting Engineer, April.

5 American Water Works Association Inc., (1971), "Water Quality and Treatment", McGraw-Hill Book Company, 1971.

6 Argue John, (1974), Regional Supervisor, Department of Local Government, Frobisher Bay N.W.T., Personal Communication.

7 Averill D. W. and Heinke G. W., (1974), "Vacuum Sewers and Their Possible Canadian Applications", Canadian Journal of Civil Engineering, Vol 1, September.

8 Babbett J. G. et al, (1956), "Arctic Environment and Intestinal Infection", American Journal of Medical Sciences, Vol 231, No. 3.

9 __________, (1972), "Baffin Region Water Supply Program: Report on Pangnirtung", W. L. Wardrop and Associates Limited Engineering Consultants, March.

10 Balanin V. V. , Borodkin B. S. and Mekanyan G. I., (1964), "Utilization of Deep Water Heat in Reservoirs

for the Maintenance of Unfrozen Areas", Transport Publishing House, Moscow, CRREL Publication AD 716306, Microfiche, 1970.

11 Beachamp E. R., (1974), "High Strength Alloy Steels For Arctic Pipelines Wigh Special Emphasis on the New Manganese-Colombium-Molybdenum Grades", Noranda Research Centre, Canada.

12 Beattie, Erickson, Martin, Gray, (1973), "Energy Budget Studies in the Arctic Over Areas Subjected to Different Levels of Vehicular Activity", Information Canada, No. R72-8873, Ottawa.

13 Bettignes C., (1973), "Energy Supply in Isolated Communities", presented at the 24th Alaskan Science Conference, University of Alaska, Fairbanks, August.

14 Boyd J. D., (1974), "Current Trends in the Development of Arctic Grade Line-Pipe Steels", presented at the meeting on Theory and Constitation of Alloys, Queens University, Kingston, Ontario, May 8-9.

15 Boyd W. L. and Boyd J. W., (1959), "Water Supply Problems at Point Barrow", American Water Works Association Journal, Vol 51, pp 890-896, July.

16 Boyd W. L. and Boyd J. W., (1967), "Microbiological Studies of Aquatic Habitats of the Area of Inuvik N.W.T.", Artic Journal, Vol 20, No. 1, pp 27-41.

17 Bradley R. S., (1972), "Seasonal Climatic Fluctuation on Baffin Island During the Period of Instrumental

Records", Institute of Arctic and Alpine Research, University of Colorado.

18 Brice et al, (1969), "Applied Numerical Methods", John Wiley & Sons Inc., Toronto.

19 __________, (1972), "Canadian Drinking Water Standards and Objectives", Joint Committee on Drinking Water Standards of the Advisory Committee on Public Health Engineering and the Canadian Public Health Association, Queens Printer, Ottawa.

20 Clark, Alter et al, (1971), "Alaskan Industry Experience in Arctic Sewage Treatment", Alaska Water Laboratory Environmental Protection Agency and Alaska Department of Health and Welfare, Working Paper #13, May.

21 Clark, Viessman, Hammer, (1971), "Water Supply and Pollution Control", International Textbook Company, Toronto.

22 Colt Industries, (1974), "Envirovac Sewage Systems", Technical Bulletin, Beloit, Wisconsin.

23 Cooper et al, (1973), "A Digest of Environmental Legislation in Canada", Canadian Industries Ltd., Montreal, May.

24 Coutts M. J. and Christianson C. D., (1974), "Extended Aeration Sewage Treatment in Cold Climates", United States Environmental Protection Agency, Corvallis, Oregon.

25 Courmier Wilf, (1974), D.P.W. foreman, Broughton Island N.W.T., Personal Communication.

26 Creery Ian, (1974), Settlement Manager, Broughton Island N.W.T., Personal Communication.

27 Dallaire G., (1975), "Tougher Pollution Laws Spur Use of Impermeable Liners", Civil Engineering A.S.C.E., pp 63-68, May.

28 Department of Transport, (1974), "Climate of the Canadian Arctic", Canadian Hydrographic Service, Marine Science Branch, p 71.

29 Dekker H. D., (1973), "A Comprehensive Review of Municipal Services to Communities Above the Tree Line in the N.W.T.", D.P.W. Records, Frobisher Bay N.W.T., Unpublished manuscript.

30 Dingman S. L., (1971), "Hydrology of the Glen Creek Watershed Tanaca River Basin Central Alaska", CRREL Research Report 297.

31 __________, (1963), "Factors to be Considered in Delineating "Arctic" and "Antarctic" in Terms of Health and Services", American Journal of Public Health and the Nations Health, Vol 58, No. 10, pp 1565-1578.

32 Fournelle H. J. et al, (1958), "A Bacterial and Parasitological Survey of Enteric Infections in an Eskimo Area", American Journal of Public Health, Vol 48, no. 11.

33 Fournelle H. J. et al, (1959), "Seasonal Study of Enteric Infections in Alaskan Eskimos", Public Health

Reports, Vol 74.

34 Frozen Sea Research Group, (1973), "Runoff from a High Arctic Watershed", Department of Environment, Marine Services Directorate, November.

35 Gamble D. J. and Janssen C. L., (1974), "Evaluating Alternative Levels of Water and Sanitation Service For Communities in the N.W.T.", Canadian Journal of Civil Engineering, Vol 1, pp 116-128, September.

36 Gamble D. J. and Jansenn T. L., (1975), "Estimating the Cost of Garbage Collection for Settlements in Northern Regions", Northern Engineer, Vol 6, No. 4, p 32.

37 Gamble D. J. and Lukomsky P., (1975), "Utilidors in the Canadian North", Canadian Journal of Civil Engineering, Vol 2, No. 2.

38 __________, (1974), "General Development Plan - Pangnirtang N.W.T.", J. L. Richards and Associates Limited Consulting Engineers and Planners, February.

39 Giroux Bob, (1974), Settlement Manager, Pangnirtang N.W.T., Personal Communication.

40 Gordon R. C., (1974), "Winter Survival of Fecal Indicator Bacteria in a Sub-Arctic Alaskan River", National Environmental Research Centre, U.S. Environmental Protection Agency, August.

41 Gordon R. C., (1970), "Monitoring the Sanitary Bacteriological Quality of Potable Water Supplies", Federal Water Quality Administration, Department of the In-

terior, Alaskan Water Laboratory, Working Paper No. 10, October 27.

42 Godfrey R. S. (1975), "1975 Means Cost Data", Robert Snow Means Company Inc., Duxbury, M.A.

43 Grainge, Edwards, Heuchart, Shaw, (1973), "Management of Waste From Arctic and Sub-Arctic Works Camps", Information Canada, R 72-10173, Ottawa.

44 Grainge J. W., (1974), "Sanitation Manual for Isolated Regions", Environmental Health Directorate, Health Protection Branch, Information Canada, OKT4-1392, Ottawa.

45 Grainge J.W. and Cameron J. J. (1975), "Sewage Lagoons in Northern Regions", Environmental Protection Agency Technology Transfer Seminar, Anchorage, Alaska, April 7-10.

46 Gray J. M., (1972), "Metallurgy of High-Strength Low-Alloy Pipeline Steels", Present and Future Possibilities, Molycarp Corporation, presented in Dallas Texas, January 18.

47 Heinke G. W., (1974), "Report on Municipal Services in Communities of the Northwest Territories", Information Canada, R72-12674, Ottawa.

48 Heinke G. W., (1973), "Bibliography of Arctic Environmental Engineering", Department of Indian Affairs and Northern Development, Publication QS-1516-000-EE-A1, Ottawa.

49 Heinke G. W. and Deans B., (1973), "Water Supply and Waste Disposal Systems for Arctic Communities", Arctic Journal of the Arctic Institute of North America, Vol 26, No. 2, pp 149-160, June.

50 Heuchart et al, (1974), "Arctic Waste Disposal", Information Canada, R72-13474, July.

51 Holden Wm. S., (1970), "Water Treatment and Examination", J. A. Churchill, London.

52 Houk J., (1974), "Freeze Damage in Water Containers", Northern Engineer, Vol 6, No. 2, pp 7-8.

53 Jespersen F., (1973), "Vacuum Sewage Transport and Treatment in Rural Areas in Denmark", Symposium on Wastewater Treatment in Cold Climates, Saskatoon, Canada.

54 Linsley and Franzini, (1972), "Water Resources Engineering", McGraw-Hill Book Company, New York.

55 McCann S. B. and Cogley J. G., (1972), "Hydrological Observations on a Small Arctic Catchment - Devon Island", Canadian Journal of Earth Sciences, Vol 9, p 361.

56 Millipore Corporation, (1973), "Biological Analysis of Water and Wastewater", Application Manual AM302, Bedford, M.A.

57 Moore E. W., (1949), "Summary of Available Data On Quality of Arctic Waters", National Research Council Committee on Sanitary Engineering and Environment, Division of Medical Science, (cited by Heinke 48).

58 Morris G. B., (1974), "Construction of Hydroelectric Projects in the North", Fenco Engineering, Toronto.

59 Myers C. E. et al, (1973), "The Alaska Village Demonstration Projects", Arctic Bulletin, Vol 1, No. 2.

60 Northern Science Research Group, (1970), "Handbook of Water Utilities Sewers and Heating Networks Designed for Settlements in Permafrost Regions", Department of Indian and Northern Development.

61 __________, (1965), "The Northwest Territories Today", A Reference Paper for the Commission on the Development of Government in the Northwest Territories, Ministry of Northern Affairs and National Resources, Ottawa.

62 __________, (1974), "Permafrost Hydrology", Proceedings of Workshop Seminar Canadian Nation Committee, Environment Canada, Ottawa.

63 Puchtler B., (1973), "Social and Economic Implications of the Alaskan Village Demonstration Projects", U.S. Environmental Protection Agency, October.

64 Reid B. H., (1973), "Alaska Village Demonstration Projects", Working Paper No. 32, United States Environmental Protection Agency, College, Alaska, October.

65 Reid B. H., (1973), "Alaska Village Demonstration Projects - First Generation of Integrated Utilities for Remote Communities", U.S. Environmental Protection Agency, October.

66 Rice E. and Alter A. J., (1975), "Waste Management in

the North", Northern Engineer, Vol 6, No. 4.

67 Rice E. and Alter A. J., (1974), "Water Supply in the North", Northern Engineer, Vol 6, No. 2, pp 10-18.

68 Sawyer and McCarty, (1967), "Chemistry for Sanitary Engineers", McGraw-Hill Book Company, Toronto.

69 Squire A. D., (1974), "Cape Dorset Water Supply", D.P.W. Records, Frobisher Bay N.W.T., unpublished manuscript.

70 __________, (1972), "Solid Waste Management in Cold Regions", Alaska Department of Health and Welfare, College, Alaska.

71 Sulli G., (1974), "Off Peak Power for Home Heating", Northern Engineer, Vol 6, No. 2, pp 7-9.

72 Targulyan Y. O., (1961), "Man-Made Structures on Water-courses With Icing and Ice Buildup", Moscow, CRREL AD715089, Microfiche, 1970.

73 Teetor S. D. and Rosanoff S., (1959), "Design Problems for Engineers - Arctic Water Supply and Sewage Disposal", Consulting Engineer, Vol 12, No. 6, pp 90-93, June.

74 Thompson C. T., (1969), "Patterns of Housekeeping Two Eskimo Settlements", Department of Indian Affairs and Northern Development, Publication No. AS-2001-000-EE-A-11, Ottawa.

75 Thomas I. A., (1975), "More Science Less Art in Tracked Vehicles", Engineering Journal, March/April.

76 Vacusan Systems, (1974), "Vacuum Transport of Sewage", Technical Bulletin, Downsview, Ontario.

77 Vieira-Ribeiro A. R., (1975), "Estimates of Snowmelt Runoff in the High Arctic", McMaster University, Hamilton, Canada.

78 White G. C., (1972), "Handbook of Chlorination", Van Nostrandt Reinhold Company, Toronto.

APPENDIX A

THE LANGELIER SATURATION INDEX

Index Factors

Temp. (°C)	Temp. (°F)	TF	Calcium Hard. (mg/l as $CaCO_3$)	CF	Total Alk. (mg/l as $CaCO_3$)	AF
0	32	0.0	5	0.3	5	0.7
3	37	0.1	25	1.0	25	1.4
8	46	0.2	50	1.3	50	1.7
12	53	0.3	75	1.5	75	1.9
16	60	0.4	100	1.6	100	2.0
19	66	0.5	150	1.8	150	2.2
24	76	0.6	200	1.9	200	2.3
29	84	0.7	300	2.1	300	2.5
34	94	0.8	400	2.2	400	2.6
41	105	0.9	800	2.5	800	2.9
56	128	1.0	1000	2.6	1000	3.0

The Langelier Saturation Index (LSI)

$$LSI = pH + TF + CF + AF - 12.1$$

LSI less than -0.5 indicates a corrosive water supply.

LSI greater than +0.5 indicates an encrusting water supply.

Example: The untreated water of the Duval River, N.W.T.

pH	is approximately 7.0	
Hardness	is approximately 5.0,	therefore CF is 0.3
Alkal.	is approximately 5.0,	therefore AF is 0.7
Temp.	is approximately 37°F	therefore TF is 0.1

$$LSI = 7.0 + 0.1 + 0.3 + 0.7 - 12.1 = -3.0$$

Therefore this water is corrosive

APPENDIX B

Reservoir Cost Estimation

The cost of a 3.0 million gallon reservoir is estimated as follows:

[1]1.5 mil gallons (excavated)	=	7,500 cu yds.
+ 3,000 cu yds. backfill	=	3,000 cu yds.
		10,500 cu yds.
Percentage of Volume as Boulders		50%

<u>Costs</u>

5,250 cu yds. boulders excavated and placed for berm		
5,250 x (21+2) x 2*	=	241,500
5,250 cu yds. stiff soil excavated and placed		
5,250 x (3+2) x 2*		52,500
3,000 cu yds. sand, gravel and rip-rap placed		
3,000 x (3.3+2) x 2*		19,800
liner installed		25,000
dewatering		10,500
thawing of permafrost		10,000
drains		5,000
planning and supervision		52,000
contingencies		40,000
TOTAL:		456,300

---

* geographical factor

1 potable water volume is assumed to be twice the excavated volume, due to construction of berms.

Yearly operating and maintenance costs	4,000
Cost per gallon (10% interest over 10 year lifespan)	2.61¢

APPENDIX C

HEAVY EQUIPMENT ON BROUGHTON ISLAND (1974)[1]

1) One Nodwell Rn 110, 1966, $26,076 to be scrapped this summer but presently serving as water carrier with 500 gal. tank.

2) One IHC 1700 5 Ton Dump Truck 4X4, 1970, $9,700.

3) One Hough Payloader with fork lift and bucket, 1966, $15,615.

4) Three Normon Trailers, 3 ton, 8 ton, and 10 ton.

5) Muskeg Bombardier 500 gal. Water Carrier, 1971, $16,710, has diesel engine and is presently required to replace present worn water carrier - it will go into service as a fire truck with the delivery of a new water carrier expected on 1974 sea lift.

6) Bombardier Personnel Carrier Model AA8, 1968, $7,100.

7) Muskeg Bombardier MS69, $13,100 - presently being used as fuel carrier to be converted to garbage truck.

8) Muskeg Bombardier 600 gal., 1973, Perkins Diesel Engine and is to be used as new fuel carrier.

9) D5 Caterpillar, 1973, $42,000.

10) Muskeg Bombardier 600 gal., 1974, to be delivered on 74 sea lift and to go into service as new water carrier.

11) Pickup truck.

12) One Bombardier Quatrack, 1973, $57,000, a 2000 gal. water carrier which broke down so much in the course of 3 trips that it is being sent back to Montreal on this coming sea lift.

13) One DW20 Scraper including tractor to pull it (very good condition - huge, excellent machine).

NOTE: The Dewline Station has bulldozers including 2 D8's as well as 2 graders, trucks and gravel crushers. The D8's are $40 per hour to rent, including operator.

---

[1]Information gained from Wilfred Courmier, D.P.W. foreman, Broughton, July, 1974.

APPENDIX D

Heavy Equipment in Pangnirtung (1974)

1. Terrain Masks - Water Tanker 1971
2. Terrain Masks - Sewage Tanker 1971
3. Muskeg Water Tanker 1970
4. Muskeg Fire Truck 1967
5. Muskeg Flat Bed Garbage Carrier 1967
6. Bombardier Snowmobile 1967
7. International Dump Truck 1970
8. Haigh Pay Loader 1966
9. Catterpillar Motor Grader 1957
10. Case 1500 - Bulldozer
11. Nodwell Rn 75 - Fuel Tanker 1964
12. Nodwell Rn 110 - Water Tanker 1963
13. I.H. Dozer TD 20 - 1970
14. John Deere 544 - Front Loader, Back Hoe - 1970
15. Champion Motor Grades 1970
16. Crew Cab 3/4 for pick-up
17. Farm Wagon
18. Wobble Wheel Compactor
19. Air Compressor - Gardner Davis
20. Concrete Mixer - Monarch

APPENDIX D

Heavy Equipment in Pangnirtung N.W.T. (1974)

-Rental Rates-

Equipment Including Operator	Rental (Dollars/Hour)
Crew Cab Truck	$ 15.00
5 yard Dump Truck	18.00
Front End Loader	20.00
Road Graders	25.00
Muskeg Flat Bed	18.00
Muskeg Water Tanker	20.00
TD 20 Tractor	35.00
Fork Lift Tractor	18.00
Terrain Masters	45.00

APPENDIX E

DOMESTIC WATER STORAGE CAPACITIES FOR BROUGHTON N.W.T. (1974)

UNIT DESCRIPTION	NO. OF UNITS	STORAGE CAPACITY	NO. OF PEOPLE BEING SERVED	DEMAND CRITERION	TOTAL DEMAND
Northern Rental Houses	57	14 @ 250 gals. 43 @ 45 gals.	total 310	800 gals./month per household	
3 Bedroom Houses (Government)	6	250	3 to 9	800 gals./month per household	
2 Bedroom Houses (Government)	2	1 @ 250 1 @ 500	2 to 4	800 gals./month per household	
Private Residence	4	2 @ 45 2 @ 250	2 to 8 2 to 8	800 gals./month per household	
Settlement Office	1	≃ 600	4 employees		
School	1	≃ 800	90 - 100 students		
Nursing Station	1	600	1 or 2		
Hudson Bay Company	1	≃ 250	4		
D.P.W. & N.C.P.C.	1	≃1000	6 employees		
Motel	1	≃ 600	sporadic - < 6		

APPENDIX F

Program GAGE

Stream Flows From Current Meter Data

Purpose: This program calculates the flow within a stream from a set of current meter observations and calibration data. It provides a consistent and accurate method of performing these calculations and yields a printout which is easily read and stored for future reference.

Method: The stream cross section is divided into trapezoids with each station forming the boundaries of these trapezoids. The velocities in each trapezoid are calculated from the appropriate calibration relationship and averaged in order to calculate flow through each trapezoid. The component flows are then summed and the results printed.

Program Deck Name: GAGE

Input: The first five cards of the data file are for a description of the gauging, then the number of calibration ranges for the current meter is entered in format 12. For example: if a meter is calibrated such that;

velocity = 1.0 + 2.0n for 0> n> 3 and

velocity = 1.5 + 2.5n for 3> n > 5 and

velocity = 2.0 + 3.0n for 5> n

there are three ranges of n. Next the boundary values are entered as 0.0, 3.0, 5.0 in format F20.6. Then constants A and B are entered in format 2F20.6 as

1.0	2.0
1.5	2.5
2.0	3.0

Finally, the gauging data are entered. For each station enter the distance to the station, the depth at that station, the number of revolutions and the time in seconds for those revolutions in format 4F15.4. The last card should be negative numbers to signal the end of the data file.

Output: The program prints all input data so that it might be checked. It also prints the velocity profile and then gives total cross sectional area, the average velocity and the total flow.

Other Decks: No other decks are required. There are two sub-routines within the program to read and pring all data.

Program GAGE

- Listing -

Comment Cards

```
   PROGRAM GAGE(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)

**************************************************************************
**************************************************************************

                 STREAM FLOWS FROM CURRENT METER DATA

       WRITTEN BY R. SUK, MCMASTER UNIVERSITY ENGINEERING, 1974.
**************************************************************************

THIS PROGRAM CALCULATES THE FLOW IN A STREAM GIVEN METER ROTATION,
   LOCATION OF METER, DEPTH AT LOCATION, AND THE METER RATING

 INPUT DATA

    FIRST ENTER ON FIVE DATA CARDS, ANY OF WHICH MAY BE LEFT BLANK,
    THE PLACE, DATE, AND THE TIME OF THE GAUGING, RIVER STAGE, AND
    YOUR NAME AND AFFILIATION.

    METER RATING IS SPECIFIED IN THE FORM V=A+BN FOR (N1 LT N LT N2)
    N IN THIS EXAMPLE IS THE METER SPEED IN REV. PER SEC. AND
    N1, N2,.... ARE LIMITING BOUNDARY VALUES

    N IN THIS EXAMPLE IS THE METER SPEED IN REVS. PER SEC. AND
    V IS THE STREAM VELOCITY
    THERE ARE USUALLY SEVERAL RANGES OF N, EACH RANGE HAVING A
    DIFFERENT SET OF CONSTANTS A,B.

    THE FIRST DATA VALUE ENTERED IS THE NUMBER OF RANGES FOR N
    IN FORMAT I1.

    THE LOWER LIMITS N1, N2,....ARE NEXT ENTERED IN FORMAT F20.6
    BEGINNING WITH 0.00 FOR N1.

    CONSTANTS A AND B ARE NEXT ENTERED FOR EACH RANGE IN
    FORMAT 2F20.6.

    X(I) IS THE DISTANCE TO THE I-TH STATION.
    D(I) IS THE DEPTH AT THE I-TH STATION.
    REVS(I) IS THE NUMBER OF REVOLUTIONS COUNTED AT THE I-TH STA.
    TIM(I) IS THE TIME FOR REVS(I) REVOLUTIONS.
    THESE FOUR VALUES ARE ENTERED LAST IN FORMAT 4F15.4 WITH THE LAST
    SET OF VALUES BEING NEGATIVE NUMBERS TO SIGNAL END OF DATA.

 SUBROUTINES

    GAGINP READS ALL THE GAUGING DATA.
    GAGOUT WRITES ALL INPUT AND CALCULATED DATA.

**************************************************************************
**************************************************************************
```

Program GAGE

- Listing Cont'd -

Coding

```
      COMMON A(9), AREA(99), B(9), D(99), D2(99)
      COMMON IDO(100), K, L, N, NPRNT, NREAD, Q(99), QTOT
      COMMON REVS(99), RPS(99), ROT(99), TIM(99), TA
      COMMON VEL(99), VELAV, WDTH(99), X(99)
C
      QTOT=0.0
      TA=0.0
      TV=0.0
C
      NREAD=5
      NPRNT=6
C
C-----READ ALL GAUGING DATA
      CALL GAGINP
      K=L-1
C-----DETERMINE POINT VELOCITIES
      DO 10 I=1,L
      DO 11 J=1,N
      IF(RPS(I).EQ.0.0) VEL(I)=0.0
      IF(RPS(I).GT.ROT(J))  VEL(I)=A(J)+B(J)*RPS(I)
   11 CONTINUE
   10 CONTINUE
      DO 12 I=1,K
C-----CALCULATE TRAPEZOIDAL AREAS
      D2(I)=(D(I)+D(I+1))/2.0
      WDTH(I)=X(I+1)-X(I)
      AREA(I)=D2(I)*WDTH(I)
      TA=TA+AREA(I)
C-----CALCULATE AVERAGE VELOCITIES
      VEL(I)=(VEL(I)+VEL(I+1))/2.
      TV=TV+VEL(I)
C-----INTEGRATE THE FLOWS
      Q(I)=VEL(I)*AREA(I)
      QTOT=Q(I)+QTOT
   12 CONTINUE
      VELAV=QTOT/TA
      CALL GAGOUT
      STOP
      END
C
      SUBROUTINE GAGINP
C
C      ENTERS AND CHECKS ALL DATA
C
      COMMON A(9), AREA(99), B(9), D(99), D2(99)
      COMMON IDO(100), K, L, N, NPRNT, NREAD, Q(99), QTOT
      COMMON REVS(99), RPS(99), ROT(99), TIM(99), TA
      COMMON VEL(99), VELAV, WDTH(99), X(99)
C
C
      L=0
      READ(NREAD,2004)  (IDO(I),I=1,100)
      READ(NREAD,2005) N
      DO 1 J=1,N
      READ(NREAD,2006) ROT(J)
    1 CONTINUE
      DO 2 K=1,N
      READ(NREAD,2007) A(K),B(K)
    2 CONTINUE
      DO 3 I=1,99
      READ(NREAD,2008) X(I),D(I),REVS(I),TIM(I)
      IF(TIM(I).EQ.0.0) TIM(I)=1000.0
      IF(D(I).LT.0.0) GO TO 4
```

Program GAGE

- Listing Cont'd -

```
      L=L+1
    3 CONTINUE
    4 CONTINUE
      DO 5 I=1,L
      RPS(I)=REVS(I)/TIM(I)
    5 CONTINUE
 2004 FORMAT(20A4)
 2005 FORMAT(I1)
 2006 FORMAT(F20.6)
 2007 FORMAT(2F20.6)
 2006 FORMAT(4F15.4)
      RETURN
      END
C
      SUBROUTINE GAGOUT
C
C      DELIVERS AND FORMATS ALL OUTPUT
C
      COMMON A(9), AREA(99), B(9), D(99), D2(99)
      COMMON IDO(100), K, L, N, NPRNT, NREAD, Q(99), QTOT
      COMMON REVS(99), RPS(99), ROT(99), TIM(99), TA
      COMMON VEL(99), VELAV, WDTH(99), X(99)
      WRITE(NPRNT,1001)
      WRITE(NPRNT,1005) (IDO(I),I=1,100)
      WRITE(NPRNT,1011)
      WRITE(NPRNT,1006) N
      WRITE(NPRNT,1007)
      DO 9 J=1,N
      WRITE(NPRNT,1008) ROT(J),A(J),B(J)
    9 CONTINUE
      WRITE(NPRNT,1009)
      DO 6 I=1,L
      WRITE(NPRNT,1010) X(I),D(I),REVS(I),TIM(I)
    6 CONTINUE
      WRITE(NPRNT,1014)
      WRITE(NPRNT,1002)
      DO 21 I=1,K
      WRITE(NPRNT,1003) I,D2(I),AREA(I),VEL(I),Q(I)
   21 CONTINUE
      WRITE(NPRNT,1012) TA
      WRITE(NPRNT,1013) VELAV
      WRITE(NPRNT,1004) QTOT
C
 1001 FORMAT(1H1,2X,34H                         -PROGRAM GAGE-,/
     12X,53H     PROGRAM CALCULATES STREAM FLOW FOR GIVEN CURRENT,/
     22X,52H     METER RATINGS AND ANY SET OF METER OBSERVATIONS,/
     32X,52H     ------------------------------------------------,/
     42X,51H          WRITTEN BY W. JAMES AND R. SUK AT       ,/
     52X,52H     MCMASTER UNIVERSITY DEPT. OF CIVIL ENGINEERING.,///)
 1002 FORMAT(10X,50H       SECT.          DEPTH          AREA          VELOCITY,
     112H        FLOW,/)
 1003 FORMAT(15X,I3,4F13.3)
 1004 FORMAT(10X,12H TOTAL FLOW=,F10.2,2X,22H CUBIC FEET PER SECOND,//)
 1005 FORMAT(1H ,20A4)
 1006 FORMAT(2X,36H THE NO. OF RANGES FOR PROP. RATING=,I3,/)
 1007 FORMAT(2X,50H     LOWER LIMIT              CONSTANT              CONSTANT,/,
     110X,41HR.P.S.                   A                     B,/)
 1008 FORMAT(8X,F8.5,14X,F8.5,9X,F8.5,//)
 1009 FORMAT(//,14X,38H        STA.        DEPTH        REVS.       TIME ,/)
 1010 FORMAT(14X,4F10.3)
 1011 FORMAT(///,9X,29H THE FOLLOWING DATA WERE READ,///)
 1012 FORMAT(//,10X,12H TOTAL AREA=,F10.2,2X,12H SQUARE FEET,//)
 1013 FORMAT(10X,12H AVG.  VEL.=,F10.2,2X,16H FEET PER SECOND,//)
 1014 FORMAT (//,9X,36H THE FOLLOWING RESULTS WERE OBTAINED,//)
      RETURN
      END
```

Program GAGE

- Sample Input Output Data -

GAUGING PERFORMED AT BRIDGE
DUVAL RIVER PANGNIRTUNG N.W.T.
JULY 12, 1974 1805
R. SUK. MCMASTER UNIVERSITY
STAGE 1.30

THE FOLLOWING DATA WERE READ

THE NO. OF RANGES FOR PROP. RATING= 3

LOWER LIMIT R.P.S.	CONSTANT A	CONSTANT B
0.00000	.20090	1.43270
.60000	.07820	1.64630
5.47000	-.55440	1.76300

STA.	DEPTH	REVS.	TIME
0.000	0.000	0.000	1000.000
2.000	.500	.400	1.000
4.000	.583	1.550	1.000
6.000	.166	.100	1.000
8.000	.705	.256	1.000
10.000	1.375	.365	1.000
12.000	.916	1.765	1.000
14.000	1.000	2.147	1.000
16.000	2.588	2.500	1.000
18.000	1.833	2.609	1.000
20.000	2.000	1.493	1.000
22.000	1.706	.602	1.000
24.000	1.542	.341	1.000
26.000	0.000	0.000	1000.000

THE FOLLOWING RESULTS WERE OBTAINED

SECT.	DEPTH	AREA	VELOCITY	FLOW
1	.250	.500	.387	.193
2	.542	1.083	1.702	1.843
3	.375	.749	1.487	1.114
4	.436	.871	.456	.397
5	1.040	2.080	.660	1.373
6	1.146	2.291	1.868	4.280
7	.958	1.916	3.295	6.320
8	1.794	3.588	3.903	14.005
9	2.211	4.421	4.284	18.938
10	1.917	3.833	3.455	13.242
11	1.854	3.708	1.803	6.684
12	1.625	3.250	.879	2.858
13	.771	1.542	.345	.532

TOTAL AREA= 29.83 SQUARE FEET

AVG. VEL.= 2.41 FEET PER SECOND

TOTAL FLOW= 71.78 CUBIC FEET PER SECOND

APPENDIX G

Program CURFIT

Rating Curves for Streamflows

Purpose: This program determines the best fit rating curve for a set of stage-discharge co-ordinates. The resultant curve is plotted against the original data points and the standard deviation and the constants of the polynomial equation describing the curve are listed.

Method: The polynomial equation is determined by a regression analysis employing the method of least mean squares. The program performs the operation for polynomials of order MIN to order MAX for either the original data points or the logs of those points, and plots each equation against the input co-ordinates or their logs and lists the standard deviation. It is then up to the user to determine which order of polynomial is most suitable.

Program Deck Name: CURFIT

Input: The first data entered is the number of co-ordinate sets in format I20. Then five cards must be used to define the given data set, discribing the data and location of the rating curve. Any of these five cards may be left blank. Then the number of stage-discharge co-ordinates, the lowest and the highest polynomial desired and NLOG are entered respectively in format 4I5. If NLOG is less than 2, CURFIT will find the polynomial regressions of the logs of stage and discharge co-ordinates. If NLOG is greater than 2, the original data points are used. Next all the values of stage and finally all the values of discharge are entered in format 6F10.5.

Output: The program will list all the input so that it may be checked. It also gives the values of the determinant, the standard deviation and the constants for each order of polynomial. S is the standard deviation and the equation for discharge is given by

$$\text{Discharge} = A + B(1) \times \text{STAGE} + B(2) \times \text{STAGE}^2 + B(3) \times \text{STAGE}^3 \ldots$$

or where the logs of stage and discharge are used

$$\text{Discharge} = 10.0^{(A + B(1) \times \text{LOG}_{10}(\text{STAGE}) + B(2) \times (\text{LOG}_{10}(\text{STAGE}))^2 + \ldots}$$

The resultant curves are also plotted against the original data points so that the degree of scatter may be examined.

Other Decks: No other decks are required. There are two functions included in CURFIT. Function REGR performs the regression analysis and it calls function SIMUL to solve sets of simultaneous equations.

Program CURFIT

- Listing -

Comment Cards

```
  PROGRAM CURFIT(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
------------------------------------------------------------------------
------------------------------------------------------------------------

      RATING CURVES FOR STREAM FLOWS

      WRITTEN BY R. SUK, MCMASTER UNIVERSITY ENGINEERING, OCTOBER 1974
      ADAPTED FROM BRICE CARNAHAN LUTHER, APPLIED NUMERICAL METHODS,
      EXAMPLE 8.5, JOHN WILEY AND SONS INC., TORONTO, 1969.

------------------------------------------------------------------------

      THIS MAIN PROGRAM READS THE HORIZONTAL AND VERTICAL COORDINATES
      OF M DATA POINTS INTO THE STAGE AND FLOW ARRAYS.  THE LEAST AND
      GREATEST VALUES OF STAGE SHOULD BE STORED IN STAGE(1) AND
      STAGE(M) RESPECTIVELY.  THE FUNCTION REGR IS USED TO PERFORM
      SUCCESSIVE NTH ORDER REGRESSIONS, FROM N=MIN THROUGH N=MAX.  IN EACH
      CASE, THE REGRESSION CURVE IS PLOTTED AGAINST THE ORIGINAL
      DATA POINTS.

  INPUT DATA

      IDO(I)     ENTER ONTO THE FIRST FIVE DATA CARDS, ANY OF WHICH
                 MAY BE LEFT BLANK, A DESCRIPTION OF THE RATING CURVE
                 GIVING PLACE, YEAR, INSTITUTION, ETC.
      IXX        THE NUMBER OF DATA SETS BEING ANALYSED
      M          THE NUMBER OF CO-ORDINATE SETS
      MIN        THE LOWEST ORDER OF THE REGRESSION EQUATION
      MAX        THE HIGHEST ORDER OF THE REGRESSION EQUATION
      NLOG       IF LESS THAN 2 THE PROGRAM WILL FIND THE POLYNOMIAL
                 REGRESSIONS OF THE LOGS OF THE STAGE AND DISCHARGE
                 CO-ORDINATES
      FLOW(I)    THE ARRAY OF M DISCHARGE CO-ORDINATES
      STAGE(I)   THE ARRAY OF M STAGE CO-ORDINATES

  FUNCTIONS USED

      SIMUL      SOLVES SIMULTANEOUS EQUATIONS
      REGR       PERFORMS N-TH ORDER REGRESSIONS

------------------------------------------------------------------------
------------------------------------------------------------------------
```

Coding

```
      DIMENSION STAGE(100), FLOW(100)
      DIMENSION B(10), POINT(10)
      DIMENSION SV(100)
      DIMENSION IDO(100)

      NREAD=5
      NPRNT=6
      ICX=0.0
C --------INPUT-----READING
      READ(NREAD,105) (IDO(I),I=1,100)
```

Program CURFIT

- Listing Cont'd -

```
      READ(NREAD,99) IXX
    1 CONTINUE
      IF (ICX.EQ.IXX) GO TO 8
      READ(NREAD,100) M,MIN,MAX,NLOG
      READ(NREAD,102) (STAGE(I),I=1,M)
      READ(NREAD,102) (FLOW(I),I=1,M)
      ICX=ICX+1
C          INPUT-----WRITING
      WRITE(NPRNT,205)
      WRITE(NPRNT,208) (IDO(I),I=1,100)
      WRITE(NPRNT,209)
      WRITE(NPRNT,200) M, (STAGE(I),FLOW(I),I=1,M)
      WRITE(NPRNT,201) MIN, MAX
      IF(NLOG.GT.2) GO TO 33
      DO 43 I=1,M
      STAGE(I)=ALOG10(STAGE(I))
      FLOW(I)=ALOG10(FLOW(I))
   43 CONTINUE
   33 CONTINUE
      DO 5 N=MIN,MAX
      WRITE(NPRNT,202) N
C
C     ..... USE FUNCTION REGR TO PERFORM NTH-ORDER REGRESSION .....
      S=REGR(M,STAGE,FLOW,N,A,B)
      IF (S .NE. 0.0) GO TO 3
      WRITE(NPRNT,203)
         GO TO 1
    3 CONTINUE
      WRITE(NPRNT,204) S,A,(I,B(I),I=1,N)
C
C     ..... COMPUTE 26 POINTS LYING ON REGRESSION CURVE .....
      DELTAX=(STAGE(M)-STAGE(1))/25.0
      MP1 = M + 1
      MP26 = M + 26
      DO 4  I = MP1, MP26
      STEPS = I - M - 1
      STAGE(I)=STAGE(1)+STEPS*DELTAX
      FLOW(I)=A
      DO 4  J = 1, N
      FLOW(I)=FLOW(I)+B(J)*STAGE(I)**J
    4 CONTINUE
C
C     ..... PLOT REGRESSION CURVE AGAINST ORIGINAL POINTS .....
      NN=4
      DO  30  I=1, MP26
      IF(I.GT.M)  NN=2
      CALL PLOTPT(STAGE(I),FLOW(I),NN)
   30 CONTINUE
      CALL OUTPLT
      IF(NLOG.GT.2) GO TO 35
      WRITE(NPRNT,207)
      GO TO 77
   35 CONTINUE
      WRITE(NPRNT,206)
   77 CONTINUE
    5 CONTINUE
      GO TO 1
C
C----------FORMATS-----READING
   99 FORMAT(10X,I10)
  100 FORMAT(4I5)
  102 FORMAT(6F10.5)
  105 FORMAT(20A4)
C----------FORMATS-----WRITING
  200 FORMAT(34H0 POLYNOMIAL REGRESSION, WITH M = , I2, 12H DATA POINTS,
     1 //,6X, 5HSTAGE,6X,9HDISCHARGE,//,(2F13.2))
  201 FORMAT (58H0 THE LOWEST AND HIGHEST ORDER POLYNOMIALS TO BE TRIED
     1ARE,//,6X, 7H MIN = , I3, 5X, 7H MAX = , I3)
  202 FORMAT(32H1 POLYNOMIAL REGRESSION OF ORDER,/,1H0,5X, 7H N  =  ,I3)
```

Program CURFIT

- Listing Cont'd -

```
  203 FORMAT (69H0 MATRIX C IS NEAR-SINGULAR.   REGRESSION COEFFICIENTS
     1NOT DETERMINED)
  204 FORMAT (1H0, 5X, 5H S = , F20.6/ 6X, 5H A = , F20.6//
     1 (6X, 3H B(, I2, 4H) = , F20.6))
  205 FORMAT(1H1)
  206 FORMAT (1H0, 56X, 17H ABSCISSA (STAGE))
  207 FORMAT(1H0,56X,22H ABSCISSA LOG10(STAGE))
  208 FORMAT(1H ,20A4)
  209 FORMAT(1H0,///)
C
    8 CONTINUE
      END

C          FUNCTION REGR, WHICH CARRIES OUT AN NTH-ORDER POLYNOMIAL
C          REGRESSION ON M DATA POINTS CONTAINED IN THE X AND Y ARRAYS.
C          THE FUNCTION NORMALLY RETURNS THE STANDARD DEVIATION S OF THE
C          POINTS ABOUT THE REGRESSION CURVE.  THE REGRESSION COEFFICIENTS
C          ARE PLACED IN A AND B(1)...B(N).   HOWEVER, IF THE SIMULTANEOUS
C          EQUATION SOLVING ROUTINE SIMUL ENCOUNTERS A NEAR-SINGULAR
C          MATRIX, THE FUNCTION RETURNS THE VALUE 0.0
C
      FUNCTION REGR (M, X, Y, N, A, B)
      DIMENSION C(11,11), SX(20), SYX(10), CYX(10), X(100), Y(100),
     1B(10)
      DATA EPS/ 1.0E-20/
C
C     ..... COMPUTE SUMS OF POWERS AND PRODUCTS .....
      NTWO = 2*N
      NP1 = N + 1
      SY = 0.0
      SYY = 0.0
      DO 1 I = 1, N
      NPI = N + I
      SX(I) = 0.0
      SX(NPI) = 0.0
    1 SYX(I) = 0.0
      DO 3 I = 1, M
      SY = SY + Y(I)
      SYY = SYY + Y(I)**2
      DUM = 1.0
      DO 2 J = 1, N
      DUM = DUM*X(I)
      SX(J) = SX(J) + DUM
      SYX(J)=SYX(J)+Y(I)*DUM
    2 CONTINUE
      DO 3  J = NP1, NTWO
      DUM = DUM*X(I)
      SX(J) = SX(J)+DUM
    3 CONTINUE
C
C     ..... COMPUTE COEFFICIENTS C(I,J) .....
      FM= M
      CYY = SYY - SY*SY/FM
      DO 4  I = 1, N
      CYX(I)=SYX(I)-SY*SX(I)/FM
      C(I,NP1) = CYX(I)
      DO 4  J = 1, N
      IPJ = I + J
    4 C(I,J) = SX(IPJ)  - SX(I)*SX(J)/FM
C
C     ..... CALL ON SIMUL TO SOLVE SIMULTANEOUS EQUATIONS .....
      DET = SIMUL (N, C, B, EPS, 1, 11)
      WRITE(6,200) DET
  200 FORMAT (13H0        DET = , E14.8)
      IF (DET .NE. 0.0) GO TO 6
         REGR = 0.0
         RETURN
C
C     ..... COMPUTE INTERCEPT A AND STANDARD DEVIATION S .....
    6 DUM = SY
```

Program CURFIT

- Listing Cont'd -

```
      TEMP = CYY
      DO 7  I = 1, N
      DUM = DUM - B(I)*SX(I)
    7 TEMP = TEMP - B(I)*CYX(I)
      A = DUM/FM
      DENOM = M - N - 1
      S=SQRT(TEMP/DENOM)
      REGR = S
      RETURN
C
      END
 FUNCTION SIMUL( N, A, X, EPS, INDIC, NRC )

   WHEN INDIC IS NEGATIVE, SIMUL COMPUTES THE INVERSE OF THE N BY
   N MATRIX A IN PLACE.  WHEN INDIC IS ZERO, SIMUL COMPUTES THE
   N SOLUTIONS X(1)...X(N) CORRESPONDING TO THE SET OF LINEAR
   EQUATIONS WITH AUGMENTED MATRIX OF COEFFICIENTS IN THE N BY
   N+1 ARRAY A AND IN ADDITION COMPUTES THE INVERSE OF THE
   COEFFICIENT MATRIX IN PLACE AS ABOVE.  IF INDIC IS POSITIVE,
   THE SET OF LINEAR EQUATIONS IS SOLVED BUT THE INVERSE IS NOT
   COMPUTED IN PLACE. THE GAUSS-JORDAN COMPLETE ELIMINATION METHOD
   IS EMPLOYED WITH THE MAXIMUM PIVOT STRATEGY.  ROW AND COLUMN
   SUBSCRIPTS OF SUCCESSIVE PIVOT ELEMENTS ARE SAVED IN ORDER IN
   THE IROW AND JCOL ARRAYS RESPECTIVELY.  K IS THE PIVOT COUNTER,
   PIVOT THE ALGEBRAIC VALUE OF THE PIVOT ELEMENT, MAX
   THE NUMBER OF COLUMNS IN A AND DETER THE DETERMINANT OF THE
   COEFFICIENT MATRIX.  THE SOLUTIONS ARE COMPUTED IN THE (N+1)TH
   COLUMN OF A AND THEN UNSCRAMBLED AND PUT IN PROPER ORDER IN
   X(1)...X(N) USING THE PIVOT SUBSCRIPT INFORMATION AVAILABLE
   IN THE IROW AND JCOL ARRAYS.  THE SIGN OF THE DETERMINANT IS
   ADJUSTED, IF NECESSARY, BY DETERMINING IF AN ODD OR EVEN NUMBER
   OF PAIRWISE INTERCHANGES IS REQUIRED TO PUT THE ELEMENTS OF THE
   JORD ARRAY IN ASCENDING SEQUENCE WHERE JORD(IROW(I)) = JCOL(I).
   IF THE INVERSE IS REQUIRED, IT IS UNSCRAMBLED IN PLACE USING
   Y(1)...Y(N) AS TEMPORARY STORAGE.  THE VALUE OF THE DETERMINANT
   IS RETURNED AS THE VALUE OF THE FUNCTION.  SHOULD THE POTENTIAL
   PIVOT OF LARGEST MAGNITUDE BE SMALLER IN MAGNITUDE THAN EPS,
   THE MATRIX IS CONSIDERED TO BE SINGULAR AND A TRUE ZERO IS
   RETURNED AS THE VALUE OF THE FUNCTION.

      DIMENSION IROW(50),JCOL(50),JORD(50),Y(50),A(NRC,NRC),X(N)
C
      MAX = N
      IF ( INDIC.GE.0 )   MAX = N + 1
C
C     .....IS N LARGER THAN 50 .....
      IF ( N.LE.50 )   GO TO 5
      WRITE (6,200)
      SIMUL = 0.
      RETURN
C
C     ..... BEGIN ELIMINATION PROCEDURE .....
    5 DETER = 1.
      DO 18    K = 1, N
      KM1 = K - 1
C
C     ..... SEARCH FOR THE PIVOT ELEMENT .....
      PIVOT = 0.
      DO 11    I = 1, N
      DO 11    J = 1, N
C     ..... SCAN IROW AND JCOL ARRAYS FOR INVALID PIVOT SUBSCRIPTS ....
      IF ( K.EQ.1 )    GO TO 9
      DO 8    ISCAN = 1, KM1
      DO 8    JSCAN = 1, KM1
      IF ( I.EQ.IROW(ISCAN) )    GO TO 11
      IF(J.EQ.JCOL(JSCAN)) GO TO 11
    8 CONTINUE
    9 IF(ABS(A(I,J)).LE.ABS(PIVOT)) GO TO 11
```

Program CURFIT

- Listing Cont'd -

```
      PIVOT = A(I,J)
      IROW(K) = I
      JCOL(K) = J
   11 CONTINUE
C
C     ..... INSURE THAT SELECTED PIVOT IS LARGER THAN EPS .....
      IF (ABS(PIVOT).GT.EPS) GO TO 13
      SIMUL = 0.
      RETURN
C
C     ..... UPDATE THE DETERMINANT VALUE .....
   13 IROWK = IROW(K)
      JCOLK = JCOL(K)
      DETER = DETER*PIVOT
C
C     ..... NORMALIZE PIVOT ROW ELEMENTS .....
      DO 14   J = 1, MAX
   14 A(IROWK,J)=A(IROWK,J)/PIVOT
C
C     ..... CARRY OUT ELIMINATION AND DEVELOP INVERSE .....
      A(IROWK,JCOLK) = 1./PIVOT
      DO 18   I = 1, N
      AIJCK = A(I,JCOLK)
      IF(I.EQ.IROWK) GO TO 18
      A(I,JCOLK) = - AIJCK/PIVOT
      DO 17   J = 1, MAX
   17 IF ( J.NE.JCOLK )   A(I,J) = A(I,J) - AIJCK*A(IROWK,J)
   18 CONTINUE
C
C     ..... ORDER SOLUTION VALUES (IF ANY) AND CREATE JORD ARRAY ....
      DO 20   I = 1, N
      IROWI = IROW(I)
      JCOLI = JCOL(I)
      JORD(IROWI) = JCOLI
   20 IF ( INDIC.GE.0 )   X(JCOLI) = A(IROWI,MAX)
C
C     ..... ADJUST SIGN OF DETERMINANT .....
      INTCH = 0
      NM1 = N - 1
      DO 22   I = 1, NM1
      IP1 = I + 1
      DO 22   J = IP1, N
      IF ( JORD(J).GE.JORD(I))   GO TO 22
      JTEMP = JORD(J)
      JORD(J) = JORD(I)
      JORD(I) = JTEMP
      INTCH = INTCH + 1
   22 CONTINUE
      IF ( INTCH/2*2.NE.INTCH )   DETER = - DETER
C
C     ..... IF INDIC IS POSITIVE RETURN WITH RESULTS .....
   24 IF ( INDIC.LE.0 )   GO TO 26
      SIMUL = DETER
      RETURN
C
C     ..... IF INDIC IS NEGATIVE OR ZERO, UNSCRAMBLE THE INVERSE
C           FIRST BY ROWS .....
   26 DO 28   J = 1, N
      DO 27   I = 1, N
      IROWI = IROW(I)
      JCOLI = JCOL(I)
   27 Y(JCOLI) = A(IROWI,J)
      DO 28   I = 1, N
   28 A(I,J) = Y(I)
C     ..... THEN BY COLUMNS .....
      DO 30   I = 1, N
      DO 29   J = 1, N
      IROWJ = IROW(J)
```

Program CURFIT

- Listing Cont'd -

```
      JCOLJ = JCOL(J)
   29 Y(IROWJ)  = A(I,JCOLJ)
      DO 30    J = 1, N
   30 A(I,J)  = Y(J)
C
C     ..... RETURN FOR INDIC NEGATIVE OR ZERO .....
      SIMUL = DETER
      RETURN
C
C     ..... FORMAT FOR OUTPUT STATEMENT .....
  200 FORMAT( 10HON TOO BIG)
C
      END
```

- Sample Input Output Data -

```
LEAST MEAN LOG REGRESSION OF RATING CURVE
FOR THE DUVAL RIVER NEAR PANGNIRTUNG N.W.T.
SUMMER 1974     -MCMASTER UNIVERSITY


POLYNOMIAL REGRESSION, WITH M =  7 DATA POINTS

       STAGE        DISCHARGE

        1.30          72.00
        1.56         142.00
        1.61         142.50
        1.77         212.00
        1.96         259.00
        2.00         335.00
        2.73         850.00

THE LOWEST AND HIGHEST ORDER POLYNOMIALS TO BE TRIED ARE

     MIN =   1       MAX =   5


POLYNOMIAL REGRESSION OF ORDER

     N  =    1

     DET = -.61748248E-01

     S =                  .028630
     A =                 1.481295

     B( 1) =               3.332762
```

APPENDIX H

Program XLIST

Stage-Discharge Tables

Purpose: XLIST produces a standard stage discharge table from the appropriate rating curve as chosen from CURFIT.

Method: The program interpolates the polynomial equation from 0.0 stage to a given miximum stage and stores and prints the calculated discharges.

Program Deck Name: XLIST

Input: The first five cards give a description of the listing. The constants A, B(1), B(2)... as obtained from CURFIT are entered in format 6F10.5. Next NLOG is entered in format I2. If NLOG is less than 2 flow is calculated as a log-log function of stage. Finally LL, the maximum stage, is entered in format I2.

Output: The program lists a stage discharge table for .01 increments of stage.

Other Decks: No other decks are required.

Program XLIST

- Listing -

Comment Cards

```
PROGRAM XLIST(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)

*************************************************************************
*************************************************************************

   THIS PROGRAM LISTS A STAGE DISCHARGE TABLE

   WRITTEN BY R. SUK, MCMASTER UNIVERSITY ENGINEERING, 1974

*************************************************************************

   THE FOLLOWING ENTRIES MUST BE MADE

   TITLE CARDS       THE FIRST FIVE DATA CARDS ARE USED TO GIVE A
                     DESCRIPTION OF THE STAGE DISCHARGE TABLE
   A,B(1),B(2),...   THE CONSTANTS WHICH DEFINE THE RATING CURVE
   NLOG              IF LESS THAN 2, FLOW IS CALCULATED AS A
                     LOG-LOG FUNCTION OF STAGE
   LL                THE MAXIMUM STAGE

*************************************************************************
*************************************************************************
```

Coding

```
      DIMENSION B(9)
      DIMENSION IDO(100)
      COMMON Q(999)
C
      NREAD=5
      NPRNT=6
C
C
C---------READ STATEMENTS
C
      READ(NREAD,1005) (IDO(I),I=1,100)
      READ(NREAD,1004) NLOG
      READ(NREAD,1004) LL
      READ(NREAD,1003) A, (B(I),I=1,5)
C
      WRITE(NPRNT,4999)
      WRITE(NPRNT,2001) (IDO(I),I=1,100)
      WRITE(NPRNT,5000)
      WRITE(NPRNT,1000)
C
      XX=.0
      X=0.0
      MIN=1
      MAX=10
      XLOW=0.0
      XLOW=XLOW-0.0001
      LIM=100*LL
C
      DO 1 I=1,LIM
      IF(X.LT.XLOW) Q(I)=-777.7
      IF(X.LT.XLOW) GO TO 5
      IF (NLOG.LT.2) GO TO 7
```

Program XLIST

- Listing Cont'd -

```
      GO TO 8
    7 CONTINUE
      Q(I)=10.0**(A+B(1)*ALOG10(X)+B(2)*(ALOG10(X))**2.0+B(3)*(ALOG10(X)
     $)**3.0+B(4)*(ALOG10(X))**4.0+B(5)*(ALOG10(X))**5)
      GO TO 5
    8 CONTINUE
      Q(I)=A+B(1)*X+B(2)*(X**2)+B(3)*(X**3)+B(4)*(X**4)+B(5)*(X**5)
    5 CONTINUE
      X=X+0.01
    1 CONTINUE
C
    6 CONTINUE
      WRITE(NPRNT,1002)
      N=0
    3 CONTINUE
      N=N+1
      WRITE(NPRNT,1001) XX, (Q(I), I=MIN,MAX), XX
      XX=XX+0.1
      MIN=MIN+10
      MAX=MAX+10
      ELL=LL
      IF(XX.GT.ELL) GO TO 4
      IF(N.EQ.5) GO TO 6
      GO TO 3
    4 CONTINUE
C
C
 1000 FORMAT(///,124H   FEET           .00            .01            .02            .03
     1         .04           .05            .06            .07            .08            .09
     1    FEET,//)
 1001 FORMAT(4X,F3.1,10F11.2,F8.1)
 1002 FORMAT(1H )
 1003 FORMAT(6F10.5)
 1004 FORMAT(I2)
 1005 FORMAT(20A4)
 1006 FORMAT(I5)
 2000 FORMAT(//,5X,20A4)
 2001 FORMAT(1H ,20A4)
 4999 FORMAT(1H1)
 5000 FORMAT(/,15X,22H STAGE-DISCHARGE TABLE,/)
      END
```

- Sample Input -

NLOG = 1

LL = 4

A = 1.48129

B(1) = 3.33276

OUVAL RIVER
PANGNIRTUNG N.W.T.
1974

STAGE-DISCHARGE TABLE

FEET	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09	FEET
0.0	153.05	149.19	145.37	141.60	137.88	134.21	130.58	127.00	123.47	119.98	0.0
.1	116.54	113.15	109.81	106.51	103.26	100.05	96.90	93.79	90.73	87.71	.1
.2	84.74	81.82	78.95	76.12	73.34	70.61	67.93	65.29	62.70	60.15	.2
.3	57.66	55.21	52.81	50.45	48.14	45.88	43.67	41.50	39.38	37.31	.3
.4	35.29	33.31	31.36	29.49	27.66	25.87	24.12	22.43	20.78	19.18	.4
.5	17.62	16.12	14.66	13.24	11.88	10.56	9.29	8.06	6.89	5.75	.5
.6	4.67	3.64	2.65	1.71	.81	-.04	-.84	-1.59	-2.29	-2.95	.6
.7	-3.57	-4.13	-4.65	-5.12	-5.54	-5.92	-6.25	-6.53	-6.76	-6.95	.7
.8	-7.09	-7.19	-7.23	-7.23	-7.18	-7.05	-6.89	-6.70	-6.52	-6.24	.8
.9	-5.91	-5.53	-5.11	-4.63	-4.11	-3.55	-2.94	-2.28	-1.57	-.81	.9
1.0	-.01	.84	1.73	2.68	3.67	4.70	5.79	6.92	8.10	9.32	1.0
1.1	10.60	11.92	13.26	14.70	16.16	17.67	19.22	20.83	22.48	24.17	1.1
1.2	25.92	27.71	29.55	31.43	33.36	35.34	37.37	39.44	41.56	43.73	1.2
1.3	45.95	48.21	50.52	52.88	55.28	57.73	60.23	62.77	65.37	68.00	1.3
1.4	70.69	73.42	76.21	79.03	81.91	84.83	87.80	90.81	93.86	96.99	1.4
1.5	100.15	103.35	106.60	109.90	113.25	116.64	120.08	123.57	127.10	130.68	1.5
1.6	134.31	137.99	141.71	145.48	149.30	153.16	157.07	161.03	165.04	169.09	1.6
1.7	173.19	177.34	181.53	185.77	190.05	194.40	198.78	203.21	207.69	212.21	1.7
1.8	216.78	221.40	226.06	230.78	235.54	240.34	245.20	250.10	255.04	260.04	1.8
1.9	265.08	270.17	275.31	280.49	285.72	291.00	296.32	301.70	307.12	312.58	1.9
2.0	318.10	323.66	329.26	334.92	340.62	346.37	352.16	358.01	363.90	369.84	2.0
2.1	375.82	381.85	387.93	394.06	400.23	406.45	412.72	419.03	425.39	431.80	2.1
2.2	438.26	444.76	451.31	457.91	464.55	471.24	477.98	484.77	491.60	498.48	2.2
2.3	505.41	512.38	519.40	526.47	533.58	540.75	547.96	555.21	562.52	569.87	2.3
2.4	577.27	584.71	592.20	599.74	607.33	614.96	622.64	630.37	638.15	645.97	2.4
2.5	653.84	661.75	669.72	677.73	685.78	693.89	702.04	710.24	718.49	726.78	2.5
2.6	735.12	743.51	751.94	760.42	768.95	777.53	786.15	794.82	803.54	812.30	2.6
2.7	821.12	829.97	838.88	847.83	856.83	865.88	874.97	884.12	893.30	902.54	2.7
2.8	911.82	921.15	930.53	939.95	949.42	958.94	968.51	978.12	987.78	997.49	2.8
2.9	1007.24	1017.04	1026.89	1036.78	1046.73	1056.72	1066.75	1076.84	1086.97	1097.15	2.9
3.0	1107.37	1117.64	1127.96	1138.33	1148.74	1159.20	1169.71	1180.27	1190.87	1201.52	3.0
3.1	1212.21	1222.96	1233.75	1244.58	1255.47	1266.40	1277.38	1288.41	1299.48	1310.60	3.1
3.2	1321.77	1332.96	1344.24	1355.55	1366.91	1378.31	1389.76	1401.26	1412.80	1424.39	3.2
3.3	1436.03	1447.72	1459.45	1471.23	1483.06	1494.93	1506.85	1518.82	1530.84	1542.90	3.3
3.4	1555.01	1567.16	1579.37	1591.62	1603.92	1616.26	1628.66	1641.10	1653.58	1666.12	3.4
3.5	1678.70	1691.32	1704.00	1716.72	1729.49	1742.31	1755.17	1768.08	1781.04	1794.04	3.5
3.6	1807.10	1820.20	1833.34	1846.54	1859.78	1873.06	1886.40	1899.78	1913.21	1926.69	3.6
3.7	1940.21	1953.78	1967.40	1981.06	1994.77	2008.53	2022.34	2036.19	2050.09	2064.04	3.7

APPENDIX I

Program HCNA

Hardy Cross Network Analysis

Purpose: This program determines the directions and magnitudes of flows in a network of pipes and the corresponding head losses. The trial and error application of this analysis enables the determination of the appropriate pipe sizes to be used in networks such as water supply systems.

Method: HCNA uses the standard Hardy Cross Analysis, incremementing flows until head losses are balanced. The program was adapted from an existing program in the personal library of Dr. William James and was elaborated to be more easily applied and interpretted. The logic and accuracy of the program were proved by testing it against worked examples of network analysis found in Schaum's Outline Series, "Theory and Problems of Fluid Mechanics and Hydraulics", Second Edition, Ranald V. Giles, McGraw-Hill, 1962.

Program Deck Name: HCNA

Input: The first card is used to give a description of the network being analysed. Next, EPSLN, the order of accuracy required in the flow increments is entered in format F10.5. Next, M and N, the number of loops and pipes are centered in format I3. Then the major and minor loop numbers are entered for each pipe in format 2I2. Positive flow is considered to be clockwise around a loop. In the input, the major loop is the one giving a positive flow for a given pipe. The area external to the network is considered to have zero as a loop number. Zero cannot be a major loop number. Where zero becomes one of the loop numbers for a given pipe, it must be entered as the minor loop number and flow is entered as a negative flow. Next, the estimated flows for each pipe from 1 to N are entered in format F10.5. Then the gravitation constant is entered. Finally the fraction factor for the Darcy-Weisbach equation, the length and the diameter of each pipe are entered in format 3F8.3. Diameter is entered in inches and length in feet.

Output: The program prints all the input data so that it may be checked and then lists the resulted flows, head losses and energy gradients for each pipe. Head losses are given as the total number of feet of head lost in that pipe and the energy gradient H/ZLEN is the loss given as Ft./Ft. If the sign of the flow in a pipe is opposite the one given in the initial estimate it means the flow direction is opposite to that originally assumed.

Other Decks: No other decks are required. No subroutines or functions are used.

Program HCNA

- Listing -

Comment Cards

```
PROGRAM HCNA(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OJTPUT)
---------------------------------------------------------------------
---------------------------------------------------------------------

     HARDY CROSS PIPE NETWORK ANALYSIS

     DR. W. JAMES AND R. SUK, MCMASTER UNIVERSITY, 1975

---------------------------------------------------------------------

INPUT DATA -EPSLN IS ORDER OF ACCURACY OF FLOW ESTIMATES
           -M AND N ARE NJMBER OF LOOPS AND PIPES
           -MALN AND MINLN ARE MAJAOR AND MINOR LOOPS ASSOCIATED
            WITH EACH PIPE.  POSITIVE FLOW IS CLOCKWISE AROUND
            THE MAJOR LOOP.  THE AREA OUTSIDE THE NETWORK IS
            DESIGNATED BY ZERO.  ZERO CANNOT BE A MAJOR LOOP NUMBER.
            AT LEAST ONE PIPE IN ANY ONE LOOP MUST HAVE AN INITIAL
            NON ZERO FLOW ESTIMATE.
           -FRCTN IS THE FRICTION FACTOR OF THE DARCY-WIESBACH
            EQUATION
           -Q(I) IS THE INITIAL FLOW ESTIMATE FOR A PIPE
           -DIAM(I) IS THE IS THE DIAMETER IN INCHES
           -ZLEN(I) IS THE LENGTH IN FEET
           -GRAVT IS THE APPROPRIATE GRAVITATIONAL CONSTANT

---------------------------------------------------------------------
---------------------------------------------------------------------
```

Coding

```
      DIMENSION MALN(100),MILN(100),CONST(100),Q(100)
      DIMENSION TOTN(30),TOTD(30),DQ(30)
      DIMENSION FRCTN(100),ZLEN(100),DIAM(100)
      DIMENSION HEAD(100),DH(100)
      DIMENSION IDO(20)
C
C     ---INPUT DATA -- READING
C
      READ(5,1999) (IDO(I), I=1,20)
      READ(5,1000)EPSLN
      READ(5,1010) M
      READ(5,1010) N
      READ(5,1020)(MALN(I),MILN(I),I=1,N)
      READ(5,1000)(Q(I),I=1,N)
      DO 17 I=1,N
      Q(I)=Q(I)/226800.
      Q(I)=Q(I)/2.
   17 CONTINUE
      READ(5,702) GRAVT
      READ (5,700)(FRCTN(I),ZLEN(I),DIAM(I),I=1,N)
C
C     CALCULATING PIPE CONSTANT (CONST)
      DO 1 I=1,N
      CONST(I)=0.810569*FRCTN(I)*ZLEN(I)/DIAM(I)**5.0/GRAVT
    1 CONST(I)=(12.**5.0)*CONST(I)
C
C
C     ---INPUT DATA -- WRITING
```

Program HCNA

- Listing Cont'd -

```
C
      WRITE(6,599)
      WRITE(6,2999)  (IDO(I),I=1,20)
      WRITE(6,900)EPSLN,M,N
      WRITE(6,909)
      WRITE(6,910)(I,MALN(I),MILN(I),FRCTN(I),ZLEN(I),DIAM(I),CONST(I),
     *Q(I),I=1,N)
      WRITE(6,911)
C
C     INITIALISING
C
      DO 88 I=1,N
      DIAM(I)=DIAM(I)/12.
   88 CONTINUE
      NUM=0
3     NUM=NUM+1
      DO 2  J=1,M
      TOTN(J)=0.0
 2    TOTD(J)=0.0
C
C     FINDING LOOP REGISTER RUNNING TOTALS
C
      DO 7  I=1,N
      HEAD(I)=CONST(I)*Q(I)*ABS(Q(I))
      DENOM=ABS(2.0*CONST(I)*Q(I))
      J=MALN(I)
      K=MILN(I)
C
C     TOTN AND TOTD ARE THE LOOP SUMS OF NUMERATOR AND DENOMINATOR
C                   VALUES FROM PIPES
C
      TOTN(J)=TOTN(J)+HEAD(I)
      TOTD(J)=TOTD(J)+DENOM
      IF(K)7,7,6
6     TOTN(K)=TOTN(K)-HEAD(I)
      TOTD(K)=TOTD(K)+DENOM
 7    CONTINUE
      DO 9  J=1,M
      DQ(J)=-TOTN(J)/TOTD(J)
 9    CONTINUE
C
C     FINDING NEW ESTIMATES OF FLOWS
C
      DO 12 I=1,N
      J=MALN(I)
      K=MILN(I)
      IF(K)10,10,11
 10   Q(I)=Q(I)+DQ(J)
      GO TO 12
 11   Q(I)=Q(I)+DQ(J)-DQ(K)
 12   CONTINUE
C
C     TESTING TO SEE IF DQ IS ACCURATE ENOUGH.IF NOT,THEN THE ITERATION
C     IS REPEATED, PROVIDED THE NUMBER OF ITERATIONS DOES NOT EXCEED 99
C
      DO 8  J=1,M
      IF(ABS(DQ(J))-EPSLN)8,8,13
   13 IF(NUM-99)14,15,15
 14   GO TO 3
 8    CONTINUE
      GO TO 16
C
 15   WRITE(6,1050)
 16   WRITE(6,1060)NUM
      DO 89 I=1,N
   89 DH(I)=HEAD(I)/ZLEN(I)
      WRITE(6,1070)
      WRITE(6,1080)  (I,Q(I),HEAD(I),DH(I),I=1,N)
 700  FORMAT(3F6.3)
 702  FORMAT(F6.3)
```

Program HCNA

- Listing Cont'd -

```
899   FORMAT(1H1,30X,*INPUT DATA PRINTOUT*)
900   FORMAT(//1X,*EPSLN=*,F9.5,5X,*NUMBER OF LOOPS=*,I3,5X,*NUMBER OF P
     $IPES=*,I3)
909   FORMAT(/1X,*PIPE NUMBER*,3X,*MALN*,4X,*MILN*,6X,*FRCTN*,5X,*ZLEN*,
     $5X,*DIAM*,7X,*CONST*,8X,*FLOW*)
910   FORMAT(1H ,3I8,4F12.3,F12.5)
911   FORMAT(////30X,*OUTPUT DATA*//)
1000  FORMAT(F10.5)
1010  FORMAT(I3)
1020  FORMAT(2I2)
1050  FORMAT(1X,*ITERATION NOT CONVERGING,HOWEVER,PRESENT VALUES OF FLOW
     $GIVEN FOR ANALYSIS.MAYBE EPSLN IS TOO SMALL*)
1060  FORMAT(1X,*THE NUMBER OF ITERATIONS IS*,I3)
1070  FORMAT(///15X,*PIPE NUMBER*,10X,*FLOWS*,10X,*HEAD LOSS*,10X,*H/ZLE
     $N*)
1060  FORMAT(1H0,20X,I3,9X,F9.4,7X,F9.3,9X,F10.3)
1999  FORMAT(20A4)
2999  FORMAT(/,5X,20A4,/)
      STOP
      END
```

Sample Input Output Data

INPUT DATA PRINTOUT

BROUGHTON ISLAND - 20 HRS, PUMPING TIME

EPSLN= .00001

NUMBER OF LOOPS= 7 NUMBER OF PIPES= 31

MALN	MILN	FRCTN	ZLEN	DIAM	CONST	FLOW
6	0	.025	400.000	1.500	6248.672	.0297
6	7	.025	580.000	1.500	11960.575	.0209
6	0	.030	140.000	1.000	26308.109	.0110
6	5	.035	220.000	.750	203247.287	0.0000
5	6	.035	220.000	.750	203247.287	.0110
2	6	.025	250.000	1.500	5155.420	.0416
6	0	.025	250.000	1.500	5155.420	-.0451
6	0	.025	320.000	1.500	6598.938	-.0474
2	0	.035	170.000	.500	1192634.293	-.0022
1	2	.035	320.000	.500	2244956.669	.0022
2	1	.035	320.000	.500	2244958.669	.0011
2	0	.030	95.000	1.000	17851.931	.0220
2	5	.025	260.000	1.500	5361.637	.0297
5	0	.035	120.000	.750	110862.156	-.0066
3	0	.035	230.000	.500	1613564.043	-.0011
3	0	.035	230.000	.500	1613564.043	.0011
3	0	.035	180.000	.500	1262789.251	.0033
3	4	.035	370.000	.500	2595733.461	0.0000
3	5	.035	120.000	.500	841859.501	.0033
4	5	.035	120.000	.500	841659.501	.0011
5	4	.035	300.000	.500	2104648.752	.0011
4	0	.035	180.000	.500	1262789.251	.0055
5	0	.035	360.000	.750	332586.469	.0066
7	0	.035	170.000	.750	157054.722	-.0088
7	0	.035	290.000	.500	2034493.794	-.0022
7	0	.035	290.000	.500	2034493.794	.0011
7	0	.035	210.000	.500	1473254.126	.0044
1	0	.030	225.000	1.000	42280.890	.0198
1	0	.030	225.000	1.000	42280.890	.0165
1	0	.035	460.000	.500	3227128.087	.0011
1	0	.035	240.000	.500	1683719.002	-.0011

Program HCNA

- Sample Input Output Data Cont'd -

OUTPUT DATA

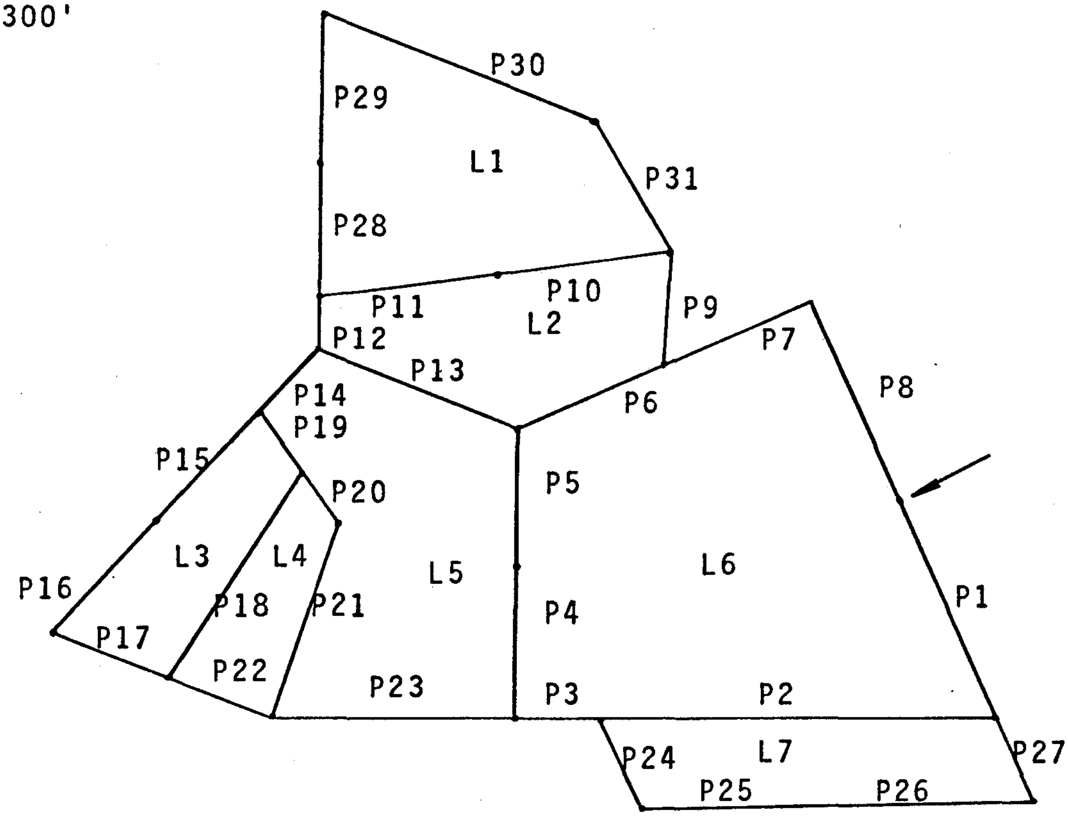
THE NUMBER OF ITERATIONS IS 10

PIPE NUMBER	FLOWS	HEAD LOSS	H/ZLEN
1	.0343	9.704	.024
2	.0255	7.791	.013
3	.0156	6.369	.045
4	.0063	7.993	.036
5	.0048	4.589	.021
6	.0357	6.556	.026
7	-.0407	-8.522	-.034
8	-.0429	-12.123	-.038
9	-.0039	-18.084	-.106
10	.0017	6.408	.020
11	.0016	5.873	.018
12	.0204	7.398	.078
13	.0298	4.764	.018
14	-.0084	-7.726	-.064
15	-.0029	-13.231	-.058
16	-.0007	-.701	-.003
17	.0015	3.017	.017
18	.0009	1.962	.005
19	.0033	9.056	.075
20	.0002	.036	.000
21	.0020	8.404	.028
22	.0029	10.481	.058
23	.0071	16.689	.046
24	-.0089	-12.329	-.073
25	-.0022	-10.266	-.035
26	.0011	2.288	.008
27	.0044	28.101	.134
28	.0176	13.152	.058
29	.0143	8.682	.039
30	-.0011	-3.921	-.009
31	-.0033	-18.412	-.077

SCHEMATIC OF PIPE NETWORK

FOR BROUGHTON ISLAND

Scale:
1" ≃ 300'



L - Loop Number

P - Pipe Number

APPENDIX J

Program SYSOPT

Optimal Design of a Pulsed Water Supply System

Purpose: This program determines the optimal design parameters for a water supply system which is insulated and electrically heated. The water may be pulsed into distributed storage or the network may operate as a normal pressure system. The program will indicate the costs or benefits involved in using various designs of insulation, pipe and electrical heating, or the costs involved with varying storage capacities or interest rates.

Method: The cost of each combination of design parameters is calculated and examined to check that it satisfies physical constraints. Only the location of the current optimal solution is stored rather than storing all possible solutions. The program integrates power usage on a monthly basis and chooses the optimal design on the basis of least annual cost for operation and borrowed capital.

Program Deck Name: SYSOPT

Input: A complete description of all the input is given in the program listing. The input parameters are listed in the order in which they must be entered.

Output: The program lists the optimal design of insulation thickness and heating strip capacity for each pipe size in the system and lists the total costs and unit costs for each diameter of pipe. Total system costs and power requirements are also listed among the output.

Program SYSOPT

Validation of Logic and Arithmetic Accuracy

Program SYSOPT was run with a simple set of extreme data in order to check the logic and arithmetic accuracy. Manual calculations were performed for a system incorporating 10,000 feet of .25 inch pipe weighing one pound per linear foot with an outside diameter of .38 inches and 100 feet of 3.00 inch pipe with a weight of 10.0 pounds per linear foot and an outside diameter of 3.5 inches. Insulation thicknesses of 0.5 or 2.0 inches were allowed and tracing tape of 8 or 24 watts was permitted. The possible warmup times were 3 or 6 hours. The other input data were as follows:

average occupancy	5.0	persons per dwelling
water demand	10.0	gallons per capita per day
pumping head	165.0	P.S.I.
flow rate	0.56	cubic feet per second
density of insulation	13.65	pounds per cubic foot
pumping time	5.0	hours
lifetime of system	20.0	years
interest on capital	10.0	percent
acceleration, gravity	32.2	feet per Sec.^{2}
duration of winter	250.0	days
operating temperature	35.0	degrees fahrenheit
conductivity of Ins.	.37	B.T.U./Hr./Ft.^{2}/inch/'F
water residue in pipes	10.0	percent
water used in storage	80.0	percent
wind factor	1.12	
energy factor	1.0	
number of months	1	
ambient temperature	-22.0	degrees fahrenheit

Hand calculations revealed that the optimal design required 0.5 inch insulation on the quarter inch line and 2.0 inch insulation on the 2.0 inch line. The best tracing tape application consisted of 8 watt tape on the small line and 24 watt tape on the larger pipe, where the cost function used was: cost = 0.15 x power. The warm-up time was 3 hours.

The results of the computer similation were in agreement with those of the hand calculations both for general results and the magnitudes of the parameters calculated.

Project SYSOPT

- Listing -

Comment Cards

PROGRAM SYSOPT(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)

```
--------------------------------------------------------------------
--------------------------------------------------------------------

     OPTIMIZATION OF A PULSED WATER SYSTEM

      WRITTEN BY R. SUK, MCMASTER UNIVERSITY ENGINEERING, 1974

--------------------------------------------------------------------

THIS PROGRAM PERFORMS AN OPTIMUM COST ANALYSIS OF A PULSED WATER
DISTRIBUTION SYSTEM THAT IS ELECTRICALLY TRACED.  THE ENTIRE
SYSTEM MAY BE ON ONE CIRCUIT, OR IF FACT4=0.0 THEN THE VARIOUS
DIAMETERS OF PIPES ARE CONSIDERED TO BE ON SEPARATE CIRCUITS TO
BE SWITCHED ON IN A TIMED SERIES.

THE FOLLOWING INPUT IS REQUIRED

  IDO            A SINGLE TITLE CARD
  AVOCC          THE AVERAGE OCCUPANCY OF THE DWELLINGS - F10.1
  DEMAND         THE WATER DEMAND PER PERSON PER DAY IN GALS. - F10.1
  HEAD           THE PUMPING HEAD IN FEET - F10.1
  Q              THE FLOW RATE IN CUBIC FEET PER SEC. - F10.1
  DENINS         THE INSULATION DENSITY IN LBS./CU.FT. - F10.1
  TPUMP          THE PUMPING INTERVAL IN HRS. - F10.1
  NINS           THE NO. OF THICKNESSES OF INSULATION TO BE TRIED - I2
  NWATT          THE NO. OF DESIGN HEAT OUTPUTS OF TRACING TAPE TO BE
                 TRIED - I2
  NTIME          THE NO. OF WARM UP TIMES TO BE TRIED - I2
  XINS(NINS)     THE VARIOUS INSULATION THICKNESSES TO BE TRIED IN
                 INCHES - 10F8.4
  WATT(NWATT)    THE VARIOUS DESIGN HEAT OUTPUTS TO BE TRIED IN WATTS
                 PER FOOT PER HOUR - 10F8.4
  TMALL(NTIME)   THE VARIOUS ALLOWABLE WARM UP TIMES TO BE TRIED IN
                 HRS. - 10F8.4
  NDIAM          THE NO. OF THE VARIOUS DIAMETERS OF PIPES IN THE
                 DISTRIBUTION SYSTEM - I2
  DIAM(NDIAM)    THE VARIOUS DIAMETERS IN INCHES - 10F8.4
  DIAMO(NDIAM)   THE OUTSIDE DIAMETERS OF THE PIPES IN INCHES - 10F8.4
  XLEN(NDIAM)    THE CORRESPONDING LENGTHS IN EACH DIAMETER IN FEET - 10F8.4
  WGHT(I)        THE CORRESPONDING WHEIGHT PER FOOT OF THE PIPES
                 IN LBS - 10F8.4
  YRS1           THE DESIGN LIFETIME OF THE PIPES AND PUMPS IN YEARS
                 - F10.1
  YRS2           THE DESIGN LIFETIME OF THE INSULATION IN YEARS
                 - F10.1
  RINT           THE INTEREST ON BORROWED CAPITOL AS PERCENT - F10.1
  G              THE FORCE OF GRAVITY IN FEET SQUARD PER SECOND - F10.1
  WPER           NO. FO DAYS PER YEAR OF SUB FREEZING WEATHER - F10.1
  TEMP           THE AVERAGE AMBIENT TEMPERATURE DURING THE FREEZING
                 PERIOD IN DEGREES FAHRENHEIT - F10.1
  TOPER          THE OPERATIONAL TEMPERATURE OF THE SYSTEM IN DEGREES
                 FAHRENHEIT - F10.1
  COND           THE CONDUCTIVITY OF THE INSULATION IN B.T.U. PER
                 SQUARE FOOT PER INCH PER DEGREE FAHRENHEIT - F10.1
  FACT1          THE ESTIMATED PERCENTAGE OF WATER LEFT IN THE PIPES
                 AFTER DRAINAGE - F10.1
  VOL            THE VOLUME OF THE STORAGE TANKS IN GALLONS - F10.1
  FACT2          THE ESTIMATED PERCENTAGE OF WATER USED FROM THE
                 STORAGE TANKS AT THE TIME OF SUPPLY - F10.1
```

```
   SPHP          THE SPECIFIC HEAT OF THE PIPE IN B.T.U. PER LB.
                 - F10.1
   SPHI          THE SPECIFIC HEAT OF THE INSULATION IN B.T.U. PER LB.
                 - F10.1
   KWCST         THE COST OF ELECTRICAL POWER IN CENTS PER KILLOWATT-HR
                 - F10.1
   TDRAIN        THE TIME TO DRAIN THE SYSTEM IN HRS. - F10.1
   FACT3         A WIND FACTOR USED IN HEAT LOSS CALCULATIONS - F10.1
   FACT4         IF SET TO ZERO THEN EACH DIAMETER PIPE IS CONSIDERED
                 TO BE ON A SEPARATE CIRCUIT - F10.1
NOTE* IF FACT4 IS ZERO THEN ONLY ONE LARGE ALLOWABLE HEAT UP TIME
SHOULD BE ENTERED

THE FOLLOWING SUBROUTINES ARE USED

   BEGIN        INITIALIZES SYSTEM PARAMETERS
   COSTAP       CALCULATES THE COST OF THE HEAT TRACING TAPE
   COSTS        DETERMINES CAPITAL AND ANNUAL COSTS
   CSPIPE       CALCULATES THE COST OF THE PIPE
   CSTINS       CALCULATES COST OF INSULATION
   CSTP         CALCULATES THE COST OF SUPPLYING POWER TO PUMP
   INSPAR       CALCULATES THE INSULATION PARAMETERS
   POWER        FINDS THE POWER REQUIREMENTS OF THE SYSTEM
   PPAR         CALCULATES PIPE PARAMETERS
   RESULT       SUMS THE OPTIMAL COSTS OF EACH PIPE
   SET          STORES THE OPTIMAL COSTS FOR A GIVEN PIPE
   SYSIN        READS ALL INPUT DATA
   SYSOT1       PRINTS ALL INPUT DATA
   SYSOT2       PRINTS THE RESULTANT NETWORK PARAMETERS
   TWARM        DETERMINES THE TIME TO WARM UP PIPE
-----------------------------------------------------------------
-----------------------------------------------------------------
```

<u>Coding</u> (Common block has been omitted from the subroutines)

```
      COMMON ANCST, ANCST1, ANCST2, ANCSTM(20), ANUCPM(20)
      COMMON AO, AREA, AREAI, AREAO, AREAP, AVOCC
      COMMON BTUICE, BTUINS, BTUPIP, BTUT, CAPCST, CI(20,20), CP(20)
      COMMON CPCSTM(20), COND, CRF, CSTAPE,CSTAPM(20), CSTINS
      COMMON CSTINM(20), CSTPIP, CSTPIM(20), CSTPP, CT(12), CSTUIM(20)
      COMMON CSTUPM(20), CSTUTM(20), DEMAND, DENINS, DENOM, DIAM(20)
      COMMON DIAMI, DIAMO(20), FACT1, FACT2, FACT3, FACT4
      COMMON G, HEAD, HP, I, IDD(100), J, K, KWCST, L
      COMMON NBEST, NDIAM, NINS, NPRNT, NREAD, NTIME, NWATT
      COMMON NMON
      COMMON PWRD, PWRDRN, PWRMM(20), PWRP, PWRR, PWRRUN, PWRUNM(20)
      COMMON PWRW, PWRWRM, Q, RATE, RATEHL, RINT, RTHLM(20),SPHI, SPHP
      COMMON TACPCS, TCSTAP
      COMMON TAPCST, TCAPCS, TDIF, TDRAIN, TARRAY(52), TENWAT, TINCST
      COMMON TMALL(20), TMPL, TOPER, TPCST, TOPL, TPUMP, TPWR, TWU
      COMMON TOTNET
      COMMON TWUM(20), VOL, VOL2, WATT(12), WATTM(20), WGHT(20), WINS
      COMMON WPER, XAREA, XAREAI, XDAYS, XINS(20), XINSM(20)
      COMMON XLEN(20), XPULSE, YRS1, YRS2
C
C
      REAL KWCST
      NREAD=5
      NPRNT=6
C
```

Program SYSOPT

- Listing Cont'd -

```
C-----READ IN ALL DATA
      CALL SYSIN
C-----PRINT THE GIVEN DATA
      CALL SYSOT1
C-----INITIALIZE PROGRAM PARAMETERS
      CALL BEGIN
C-----CALCULATE THE COST OF POWER TO THE PUMP
      CALL CSTP
      TRACK=10E9
      COUNT=1.0
      I1=1
   10 CONTINUE
      DO 6 L=I1,NTIME
      TOTNET=0.0
      DO 1 K=1,NDIAM
C-----CALCULATE THE PIPE PARAMETERS
      CALL PPAR
C-----CALCULATE THE COST OF THE PIPE
      CALL CSPIPE
      TOTAL=10E8
C-----VARY THE INSULATION THICKNESS
      DO 2 J=1,NINS
C-----CALCULATE THE INSULATION PARAMETERS
      CALL INSPAR
C-----CALCULATE THE COST OF THE INSULATION
      CALL COSTIN
C-----VARY THE DESIGN WATTAGE OF THE ELECTRICAL TRACING TAPE
      DO 3 I=1,NWATT
      CALL COSTAP
C-----CALCULATE THE POWER REQUIREMENTS
      CALL POWER
C-----DETERMINE SYSTEM ANNUAL COSTS
      CALL COSTS
      IF(ANCST.LT.TOTAL) GO TO 8
      GO TO 3
    8 CONTINUE
      TOTAL=ANCST
C-----STORE THE OPTIMAL VALUES FOR THE CURRENT PIPE SIZE
      CALL SET
    3 CONTINUE
    2 CONTINUE
      TOTNET=TOTNET+TOTAL
    1 CONTINUE
      IF(COUNT.GT.10.) GO TO 21
      IF(TOTNET.LT.TRACK) GO TO 5
      GO TO 6
    5 CONTINUE
      TRACK=TOTNET
      NBEST=L
    6 CONTINUE
      COUNT=100.
      I1=NBEST
      GO TO 10
   21 CONTINUE
C-----SUM THE SYSTEM COSTS AND POWER REQUIREMENTS
      CALL RESULT
C-----PRINT THE PARAMETERS OF THE OPTIMAL SYSTEM
      CALL SYSOT2
C
      STOP
      END
```

Program SYSOPT

- Listing Cont'd

```
      SUBROUTINE BEGIN
C
C
      FACT1=FACT1/100.
      FACT2=FACT2/100.
      RINT=RINT/100.0
      VOL2=VOL*FACT2
      RATE=AVOCC*DEMAND
      XDAYS=VOL2/RATE
C-----CALCULATE THE NUMBER OF SUPPLY PULSES IN A WINTER PERIOD
      XPULSE=WPER/XDAYS
      IF(FACT2.GE.1.0) XPULSE=1.0
C-----CALCULATE THE CAPITAL RECOVERY FACTOR
      CRF=RINT*((1.0+RINT)**YRS1)/(((1.0+RINT)**YRS1)-1.0)
      RETURN
      END

      SUBROUTINE COSTAP
C
C
C-----COSTS OBTAINED FROM CHEMELEX
      CSTAPE=0.5*WATT(I)
      IF(WATT(I).LT.4.0) CSTAPE=2.0
      IF(WATT(I).GT.6.0) CSTAPE=0.35*WATT(I)
      CSTAPE=XLEN(K)*CSTAPE
      RETURN
      END

      SUBROUTINE COSTIN
C
C
      CSTINS=CI(J,K)*XLEN(K)
      RETURN
      END

      SUBROUTINE COSTS
C
      REAL KWCST
C
      CAPCST=CSTINS+CSTPIP+CSTAPE
      ANCST1=CRF*CAPCST
      ANCST2=KWCST*TPWR/100.
      ANCST=ANCST1+ANCST2
      RETURN
      END

      SUBROUTINE CSPIPE
C
C
      CSTPIP=CP(K)*XLEN(K)
      RETURN
      END

      SUBROUTINE CSTP
C
      REAL KWCST
C
      HP=(HEAD*Q*62.4)/(550.0*0.7)
      CSTPP=(HP*(0.746)*TPUMP*KWCST*(365.0/XDAYS))/100.
      RETURN
      END
```

Program SYSOPT

- Listing Cont'd -

```
      SUBROUTINE INSPAR
C
C
      DIAMI=DIAMO(K)+2.0*XINS(J)
      AREAI=3.14159*DIAMI/12.
       XAREAI=3.14159*DIAMI**2.0/4.0/144.0
      XAREA=XAREAI-AREAO
      WINS=XAREA*DENINS
      DENOM=ALOG(AREAI/AREAP)
      AO=(AREAI-AREAP)/DENOM
      RETURN
      END
      SUBROUTINE POWER
C
      XPUL=XPULSE/(FLOAT(NMON))
      PWRW=0.0
      PWRWRM=0.0
      PWRD=0.0
      PWRDRN=0.0
      PWRR=0.0
      PWRRUN=0.0
      WUT=0.0
      HL=0.0
      DO 3 IM=1,NMON
      TDIF=TOPER-TARRAY(IM)
      BTUPIP=WGHT(K)*SPHP*TDIF
      BTUICE=AREA*FACT1*62.4*(144.5+TDIF)
      BTUINS=WINS*SPHI*TDIF
      BTUT=BTUINS+BTUPIP+BTUICE
      TENWAT=BTUT/3.41
      RATEHL=(TDIF*AO*COND*FACT3)/(XINS(J)*3.41)
      CALL TWARM
      IF(XPUL.LE.1.0) TWU=0.0
      IF(XPUL.LE.1.0) TDRAIN=0.0
C-----RESTRICT THE ALLOWABLE WARM-UP TIME
      IF(RATEHL.GT.WATT(I)) TWU=2000.
      IF(TWU.GT.TMALL(L)) TWU=2000.
      ZPWRW=WATT(I)*XLEN(K)/1000.
      IF(ZPWRW.GT.PWRW) PWRW=ZPWRW
      ZPWRWR=ZPWRW*TWU*XPUL
C------USING SELF LIMITING HEATING STRIP
      ZPWRR=0.75*WATT(I)*XLEN(K)/1000.
      IF(ZPWRR.GT.PWRR) PWRR=ZPWRR
      IF(TWU.GT.TMALL(L)) GO TO 11
      ZPWRRU=ZPWRR*(TPUMP+FACT4*(TMALL(L)-TWU))*XPUL
      GO TO 7
   11 CONTINUE
      ZPWRRU=ZPWRR*TPUMP*XPUL
    7 CONTINUE
      ZPWRD=0.75*WATT(I)*XLEN(K)/1000.
      IF(ZPWRD.GT.PWRD) PWRD=ZPWRD
      ZPWRDR=ZPWRD*TDRAIN*XPUL
      PWRWRM=PWRWRM+ZPWRWR
      PWRRUN=PWRRUN+ZPWRRU
      PWRDRN=PWRDRN+ZPWRDR
      HL=HL+RATEHL
      WUT=WUT+TWU
    3 CONTINUE
      RATEHL=HL/(FLOAT(NMON))
      TWU=WUT/(FLOAT(NMON))
      TPWR=PWRWRM+PWRRUN+PWRDRN
      RETURN
      END
```

Program SYSOPT

- Listing Cont'd -

```
      SUBROUTINE PPAR
C
C
      AREAP=3.14159*DIAMO(K)/12.
      AREA=(3.14159*DIAM(K)**2.0)/4.0/144.0
      AREAO=3.14159*DIAMO(K)**2.0/4.0/144.0
      RETURN
      END
      SUBROUTINE RESULT
C
C
      TINCST=0.0
      TAPCST=0.0
      TPCST=0.0
      TCAPCS=0.0
      TCSTAP=0.0
      TOPL=0.0
      TMPL=0.0
      DO 22 K=1,NDIAM
      TMPL=TMPL+PWRMM(K)
      TOPL=TOPL+PWRUNM(K)
      TINCST=TINCST+CSTINM(K)
      TCSTAP=TCSTAP+CSTAPM(K)
      TPCST=TPCST+CSTPIM(K)
      TCAPCS=TCAPCS+CPCSTM(K)
      TAPCST=TAPCST+ANCSTM(K)
   22 CONTINUE
      PWRP=HP*0.746
      TMPL=TMPL+PWRP
      TOPL=TOPL+PWRP
      TAPCST=TAPCST+CSTPP
      TACPCS=CRF*TCAPCS
      TOTNET=TOTNET+CSTPP
      RETURN
      END
      SUBROUTINE SET
C
CC
      CSTINM(K)=CSTINS
      CSTAPM(K)=CSTAPE
      CSTPIM(K)=CSTPIP
      WATTM(K)=WATT(I)
      TWUM(K)=TWU
      XINSM(K)=XINS(J)
      RTHLM(K)=RATEHL
      ANCSTM(K)=ANCST2
      ANUCPM(K)=ANCST2/XLEN(K)
      CSTUIM(K)=CSTINS/XLEN(K)
      CSTUPM(K)=CSTPIP/XLEN(K)
      CSTUTM(K)=CSTAPE/XLEN(K)
      CPCSTM(K)=CAPCST
      PWRMM(K)=PWRW
      PWRUNM(K)=PWRR
      RETURN
      END
      SUBROUTINE SYSIN
C
      REAL KWCST
C
      READ(NREAD,1001) (IDO(I),I=1,20)
      READ(NREAD,1004) AVOCC
      READ(NREAD,1004) DEMAND
      READ(NREAD,1004) HEAD
      READ(NREAD,1004) Q
      READ(NREAD.1004) DENINS
```

Program SYSOPT

- Listing Cont'd -

```
      READ(NREAD,1004)  TPUMP
      READ(NREAD,1002)  NINS
      READ(NREAD,1002)  NWATT
      READ(NREAD,1002)  NTIME
      READ(NREAD,1003)  (XINS(I),I=1,NINS)
      READ(NREAD,1003)  (WATT(I),I=1,NWATT)
      READ(NREAD,1003)  (TMALL(I),I=1,NTIME)
      READ(NREAD,1002)  NDIAM
      READ(NREAD,1003)  (DIAM(I),I=1,NDIAM)
      READ(NREAD,1003)  (DIAMO(I),I=1,NDIAM)
      READ(NREAD,1003)  (XLEN(I),I=1,NDIAM)
      READ(NREAD,1003)  (WGHT(I),I=1,NDIAM)
      DO 75 K=1,NDIAM
   75 READ(NREAD,1003)  (CI(J,K),J=1,NINS)
      READ(NREAD,1003)  (CP(I),I=1,NDIAM)
      READ(NREAD,1004)  YRS1
      READ(NREAD,1004)  YRS2
      READ(NREAD,1004)  RINT
      READ(NREAD,1004)  G
      READ(NREAD,1004)  WPER
      READ(NREAD,1004)  TOPER
      READ(NREAD,1004)  COND
      READ(NREAD,1004)  FACT1
      READ(NREAD,1004)  VOL
      READ(NREAD,1004)  FACT2
      READ(NREAD,1004)  SPHP
      READ(NREAD,1004)  SPHI
      READ(NREAD,1004)  KWCST
      READ(NREAD,1004)  TDRAIN
      READ(NREAD,1004)  FACT3
      READ(NREAD,1004)  FACT4
      READ(NREAD,1002)  NMON
      READ(NREAD,1004)  (TARRAY(I),I=1,NMON)
C
 1001 FORMAT(20A4)
 1002 FORMAT(I2)
 1003 FORMAT(10F6.4)
 1004 FORMAT(F10.1)
C
      RETURN
      END
      SUBROUTINE SYSOT1
C
      REAL KWCST
C
      WRITE(NPRNT,2001)
      WRITE(NPRNT,2999)  (IDO(I),I=1,20)
      WRITE(NPRNT,2004)  (DIAM(I),I=1,NDIAM)
      WRITE(NPRNT,2135)  (DIAMO(I),I=1,NDIAM)
      WRITE(NPRNT,2005)  (XLEN(I),I=1,NDIAM)
      WRITE(NPRNT,2006)  (WGHT(I),I=1,NDIAM)
      WRITE(NPRNT,2026)  (WATT(I),I=1,NWATT)
      WRITE(NPRNT,2027)  (TMALL(I),I=1,NTIME)
      WRITE(NPRNT,2028)  (XINS(I),I=1,NINS)
      WRITE(NPRNT,2034)  TPUMP
      WRITE(NPRNT,2029)  AVOCC
      WRITE(NPRNT,2030)  DEMAND
      WRITE(NPRNT,2031)  HEAD
      WRITE(NPRNT,2032)  Q
      WRITE(NPRNT,2003)  NDIAM
      WRITE(NPRNT,2025)  NINS
      WRITE(NPRNT,2024)  NTIME
      WRITE(NPRNT,2023)  NWATT
      WRITE(NPRNT,2007)  SPHP
      WRITE(NPRNT,2008)  YRS1
      WRITE(NPRNT,2009)  SPHI
      WRITE(NPRNT,2033)  DENINS
      WRITE(NPRNT,2010)  YRS2
```

```
      WRITE(NPRNT,2011)  COND
      WRITE(NPRNT,2013)  FACT1
      WRITE(NPRNT,2015)  TOPER
      WRITE(NPRNT,2016)  DEMAND
      WRITE(NPRNT,2017)  VOL
      WRITE(NPRNT,2018)  FACT2
      WRITE(NPRNT,2019)  TDRAIN
      WRITE(NPRNT,2020)  WPER
      WRITE(NPRNT,2021)  KWCST
      WRITE(NPRNT,2022)  FACT3
      WRITE(NPRNT,2040)  FACT4
      WRITE(NPRNT,2014)
      WRITE(NPRNT,2140)  (TARRAY(I),I=1,NMON)
C
C     ----------FORMAT STATEMENTS -----INPUT
C
 2001 FORMAT(1H1,30X,19HINPUT DATA PRINTOUT,/)
 2003 FORMAT(/,5X,40HTHE NUMBER OF PIPE DIAMETERS                     =,I2)
 2004 FORMAT(/,5X,20HTHE DIAMETERS        =,8F10.3)
 2005 FORMAT(/,5X,20HTHE LENGTHS          =,8F10.1)
 2006 FORMAT(/,5X,20HTHE WGHT PER FOOT    =,8F10.3)
 2007 FORMAT(/,5X,40HTHE SPECIFIC HEAT OF THE PIPE                    =,F8.3)
 2008 FORMAT(/,5X,40HTHE LIFETIME OF THE PIPE                         =,F8.3)
 2009 FORMAT(/,5X,40HTHE SPECIFIC HEAT OF THE INSULATION              =,F8.3)
 2010 FORMAT(/,5X,40HTHE LIFETIME OF THE INSULATION                   =,F8.3)
 2011 FORMAT(/,5X,40HTHE CONDUCTIVITY OF THE INSULATION               =,F8.3)
 2013 FORMAT(/,5X,40HTHE AMOUNT OF WATER REMAINING                    =,F8.3,7HPER
     $CENT)
 2014 FORMAT(//,5X, 28HMONTHLY AMBIENT TEMPERATURES,/)
 2015 FORMAT(/,5X,40HTHE OPERATING TEMPERATURE                        =,F8.3)
 2016 FORMAT(/,5X,40HTHE WATER DEMAND                                 =,F8.3)
 2017 FORMAT(/,5X,40HTHE SIZE OF THE TANK                             =,F8.3)
 2018 FORMAT(/,5X,40HTHE AMOUNT OF STORAGE USED                       =,F8.3,
     $7HPERCENT)
 2019 FORMAT(/,5X,40HTHE TIME TO DRAIN                                =,F8.3,
     $4HHRS.)
 2020 FORMAT(/,5X,40HTHE LENGTH OF THE WINTER PERIOD                  =,F8.3,
     $4HDAYS)
 2021 FORMAT(/,5X,40HTHE COST OF POWER                                =,F8.3,
     $13HCENTS PER KWH)
 2022 FORMAT(/,5X,40HTHE WIND FACTOR                                  =,F8.3)
 2023 FORMAT(/,5X,40HTHE VARIETY OF ENRGY INPUTS                      =,I2)
 2024 FORMAT(/,5X,40HTHE NO. OF WARM-UP TIMES CONSIDERED              =,I2)
 2025 FORMAT(/,5X,40HTHE NUMBER OF INSUL. THICKNESSES                 =,I2)
 2026 FORMAT(/,5X,20HTHE DESIGN WATTAGES=,8F10.3)
 2027 FORMAT(/,5X,20HTHE WARM-UP TIMES   =,8F10.3)
 2028 FORMAT(/,5X,20HINSUL. THICKNESSES =,8F10.3)
 2029 FORMAT(/,5X,40HTHE AVERAGE OCCUPANCY                            =,F8.3)
 2030 FORMAT(/,5X,40HTHE DEMAND PER PERSON PER DAY                    =,F8.3)
 2031 FORMAT(/,5X,40HTHE PUMPIN HEAD                                  =,F8.3)
 2032 FORMAT(/,5X,40HTHE FLOW RATE                                    =,F8.3)
 2033 FORMAT(/,5X,40HTHE DENSITY OF INSULATION                        =,F8.3)
 2034 FORMAT(/,5X,40HTHE DURATION OF PUMPING                          =,F8.3)
 2040 FORMAT(/,5X,40HTHE SYSTEM FACTOR                                =,F8.3)
 2135 FORMAT(/,5X,20HOUTSIDE DIAMETER    =,8F10.3)
 2140 FORMAT(1H ,12X,F7.2)
 2999 FORMAT(/,5X,20A4,/)
C
      RETURN
      END

      SUBROUTINE SYSOT2
C
      REAL KWCST
C
      WRITE(NPRNT,2100)
      WRITE(NPRNT,2999)  (IDO(I),I=1,20)
      WRITE(NPRNT,2101)  TPUMP
      WRITE(NPRNT,2103)  XDAYS
```

Program SYSOPT

- Listing Cont'd -

```
      WRITE(NPRNT,2104)  XPULSE
      WRITE(NPRNT,2105)  TMALL(NBEST)
      WRITE(NPRNT,2106)  (DIAM(I),I=1,NDIAM)
      WRITE(NPRNT,2107)  (XLEN(I),I=1,NDIAM)
      WRITE(NPRNT,2108)  (XINSM(I),I=1,NDIAM)
      WRITE(NPRNT,2109)  (WATTM(I),I=1,NDIAM)
      WRITE(NPRNT,2133)  (RTHLM(I),I=1,NDIAM)
      WRITE(NPRNT,2110)  (TWUM(I),I=1,NDIAM)
      WRITE(NPRNT,2111)  (PWRMM(I),I=1,NDIAM)
      WRITE(NPRNT,2112)  (PWRUNM(I),I=1,NDIAM)
      WRITE(NPRNT,2113)  (CSTPIM(I),I=1,NDIAM)
      WRITE(NPRNT,2114)  (CSTUPM(I),I=1,NDIAM)
      WRITE(NPRNT,2115)  (CSTINM(I),I=1,NDIAM)
      WRITE(NPRNT,2116)  (CSTUIM(I), I=1,NDIAM)
      WRITE(NPRNT,2117)  (CSTAPM(I),I=1,NDIAM)
      WRITE(NPRNT,2118)  (CSTUTM(I),I=1,NDIAM)
      WRITE(NPRNT,2119)  (CPCSTM(I),I=1,NDIAM)
      WRITE(NPRNT,2120)  (ANCSTM(I),I=1,NDIAM)
      WRITE(NPRNT,2121)  (ANUCPM(I),I=1,NDIAM)
      WRITE(NPRNT,2134)
      WRITE(NPRNT,2128)  HP
      WRITE(NPRNT,2129)  CSTPP
      WRITE(NPRNT,2130)  PWRP
      WRITE(NPRNT,2122)  TINCST
      WRITE(NPRNT,2123)  TCSTAP
      WRITE(NPRNT,2124)  TPCST
      WRITE(NPRNT,2125)  TCAPCS
      WRITE(NPRNT,2126)  TACPCS
      WRITE(NPRNT,2127)  TAPCST
      WRITE(NPRNT,2136)  TOTNET
      WRITE(NPRNT,2131)  TMPL
      WRITE(NPRNT,2132)  TOPL
C
C     ----------FORMAT STATEMENTS -----OUTPUT
C
 2100 FORMAT(1H1,//,5X,44HOPTIMAL DESIGN OF PULSED WATER SUPPLY SYSTEM,/
     $)
 2101 FORMAT(///,5X,35HDURATION OF PUMPING PERIOD              =,F8.3)
 2103 FORMAT(/,5X,35HTHE NUMBER OF DAYS BETWEEN PULSES =,F8.3)
 2104 FORMAT(/,5X,35HNO. OF PULSES PER YEAR                =,F8.3)
 2105 FORMAT(/,5X,35HTHE BEST ALLOWABLE WARM-UP TIME    =,F8.3)
 2106 FORMAT(///,5X,21HPIPE DIAMETER        =,11F9.3)
 2107 FORMAT(/,5X,21HTOTAL LENGTH        =,11F9.1)
 2108 FORMAT(/,5X,21HINSUL. THICKNESS    =,11F9.3)
 2109 FORMAT(/,5X,21HDESIGN WATTAGE      =,11F9.3)
 2110 FORMAT(/,5X,21HAVG. WARM-UP TIME   =,11F9.3)
 2111 FORMAT(/,5X,21HMAX. KW LOAD-WARM   =,11F9.3)
 2112 FORMAT(/,5X,21HMAX. KW LOAD-PUMPING=,11F9.3)
 2113 FORMAT(/,5X,21HCOST OF PIPE        =,11F9.1)
 2114 FORMAT(/,5X,21HCOST PER UNIT LENGTH=,11F9.2)
 2115 FORMAT(/,5X,21HCOST OF INSULATION  =,11F9.1)
 2116 FORMAT(/,5X,21HCOST PER UNIT LENGTH=,11F9.2)
 2117 FORMAT(/,5X,21HCOST OF HEATING TAPE=,11F9.1)
 2118 FORMAT(/,5X,21HCOST PER UNIT LENGTH=,11F9.2)
 2119 FORMAT(/,5X,21HTOTAL CAPITAL COST  =,11F9.1)
 2120 FORMAT(/,5X,21HANNUAL COST OF POWER=,11F9.1)
 2121 FORMAT(/,5X,21HCOST PER UNIT LENGTH=,11F9.2)
 2122 FORMAT(///,5X,25HTOTAL INSULATION COST    =,F10.2)
 2123 FORMAT(/,5X,25HTOTAL HEATING TAPE COST =,F10.2)
 2124 FORMAT(/,5X,25HTOTAL PIPE COST           =,F10.2)
 2126 FORMAT(/,5X,25HANNUAL COST OF CAPITAL   =,F10.2)
 2125 FORMAT(/,5X,25HTOTAL CAPITAL COST        =,F10.2)
 2127 FORMAT(/,5X,25HANNUAL COST OF POWER      =,F10.2)
 2128 FORMAT(///,5X,25HPUMPING HORSEPOWER        =,F10.2)
 2129 FORMAT(/,5X,25HCOST OF POWER TO PUMP    =,F10.2)
 2130 FORMAT(/,5X,25HPOWER LOAD OF PUMP        =,F10.2)
 2131 FORMAT(///,5X,25HTOTAL MAX. PWR. LOAD     =,F10.2)
 2132 FORMAT(/,5X,25HTOTAL MAX. PUMPING LOAD =,F10.2)
 2133 FORMAT(/,5X,21HAVG. RATE HEAT-LOSS =,11F9.3)
 2134 FORMAT(1H1,///)
```

Program SYSOPT

- Listing Cont'd -

```
 2136 FORMAT(/,5X,25HTOTAL ANNUAL COST         =,F10.2)
 2999 FORMAT(/,5X,20A4,/)
      RETURN
      END

      SUBROUTINE TWARM
C
C
      TWU=TENWAT/(WATT(I)-0.5*RATEHL)
C-----ASSIGN A PENALTY IF THE RATE OF HEAT LOSS IS GREATER THAN THE
C-----RATE OF ENERGY INPUT
      IF(RATEHL.GE.WATT(I)) TWU=1000.
      RETURN
      END
```

Program SYSOPT

\- Sample Input Output Data -

```
                         INPUT DATA PRINTOUT

   BROUGHTON ISLAND N.W.T.    -    20 HRS. PUMPING TIME

THE DIAMETERS       =      .364      .622      .824     1.049     1.610     2.067     2.469     3.068
THE DIAMETERS       =     3.548
OUTSIDE DIAMETER    =      .540      .840     1.050     1.315     1.900     2.375     2.875     3.500
OUTSIDE DIAMETER    =     4.000
THE LENGTHS         =    1000.0    8250.0    1190.0    1175.0    2060.0       0.0    2650.0      -0.0
THE LENGTHS         =      -0.0
THE WGHT PER FOOT   =      .425      .851     1.131     1.679     2.718     3.653     5.793     7.576
THE WGHT PER FOOT   =     9.109
THE DESIGN WATTAGES=      2.000     3.000     4.000     5.000     6.000     7.000     8.000     9.000
THE DESIGN WATTAGES=     10.000    12.000
THE WARM-UP TIMES   =    10.000
INSUL. THICKNESSES =       .500      .625      .750      .875     1.000     1.250     1.500     2.000
THE DURATION OF PUMPING                  =  20.000
THE AVERAGE OCCUPANCY                    =   5.000
THE DEMAND PER PERSON PER DAY            =  10.000
THE PUMPIN HEAD                          = 120.000
THE FLOW RATE                            =     .077
THE NUMBER OF PIPE DIAMETERS             = 9
THE NUMBER OF INSUL. THICKNESSES         = 8
THE NO. OF WARM-UP TIMES CONSIDERED      = 1
THE VARIETY OF ENRGY INPUTS              =10
THE SPECIFIC HEAT OF THE PIPE            =     .120
THE LIFETIME OF THE PIPE                 =  15.000
```

Program SYSOPT

- Sample Input Output Data Cont'd -

THE SPECIFIC HEAT OF THE INSULATION	=	.350
THE DENSITY OF INSULATION	=	2.200
THE LIFETIME OF THE INSULATION	=	10.000
THE CONDUCTIVITY OF THE INSULATION	=	.130
THE AMOUNT OF WATER REMAINING	=	10.000PERCENT
THE OPERATING TEMPERATURE	=	40.000
THE WATER DEMAND	=	10.000
THE SIZE OF THE TANK	=	250.000
THE AMOUNT OF STORAGE USED	=	80.000PERCENT
THE TIME TO DRAIN	=	1.500HRS.
THE LENGTH OF THE WINTER PERIOD	=	270.000DAYS
THE COST OF POWER	=	18.000CENTS PER KWH
THE WIND FACTOR	=	1.000
THE SYSTEM FACTOR	=	0.000

MONTHLY AMBIENT TEMPERATURES

```
-50.00
-25.00
-17.00
-15.00
  0.00
  3.00
 13.00
 15.00
 17.00
```

Program SYSOPT

- Sample Input Output Data Cont'd -

OPTIMAL DESIGN OF PULSED WATER SUPPLY SYSTEM

BROUGHTON ISLAND N.W.T. - 20 HRS. PUMPING TIME

DURATION OF PUMPING PERIOD = 20.000
THE NUMBER OF DAYS BETWEEN PULSES = 4.000
NO. OF PULSES PER YEAR = 67.500
THE BEST ALLOWABLE WARM-UP TIME = 10.000

PIPE DIAMETER =	.364	.622	.824	1.049	1.610	2.057	2.469
TOTAL LENGTH =	1000.0	6250.0	1190.0	1175.0	2060.0	0.0	2650.0
INSUL. THICKNESS =	.500	.625	.875	1.000	.875	.500	1.250
DESIGN WATTAGE =	2.000	2.000	2.000	2.000	3.000	2.000	5.000
AVG. RATE HEAT-LOSS =	.887	1.020	.947	1.005	1.423	2.645	1.485
AVG. WARM-UP TIME =	.736	1.714	2.490	3.893	4.647	1336.084	5.392
MAX. KW LOAD-WARM =	2.000	16.500	2.380	2.350	6.180	0.000	13.250
MAX. KW LOAD-PUMPING=	1.500	12.375	1.785	1.763	4.635	0.000	9.938
COST OF PIPE =	430.0	3877.5	654.5	893.0	2492.6	0.0	7155.0
COST PER UNIT LENGTH=	.43	.47	.55	.76	1.21	I	2.70
COST OF INSULATION =	600.0	7425.0	1606.5	1880.0	3090.0	0.0	6227.5
COST PER UNIT LENGTH=	.60	.90	1.35	1.60	1.50	I	2.35
COST OF HEATING TAPE=	2000.0	16500.0	2380.0	2350.0	4120.0	0.0	6625.0
COST PER UNIT LENGTH=	2.00	2.00	2.00	2.00	2.00	I	2.50
TOTAL CAPITAL COST =	3030.0	27802.5	4641.0	5123.0	9702.6	0.0	20007.5
ANNUAL COST OF POWER=	409.7	3576.3	538.3	571.6	1559.7	0.0	3464.0
COST PER UNIT LENGTH=	.41	.43	.45	.49	.76	I	1.31

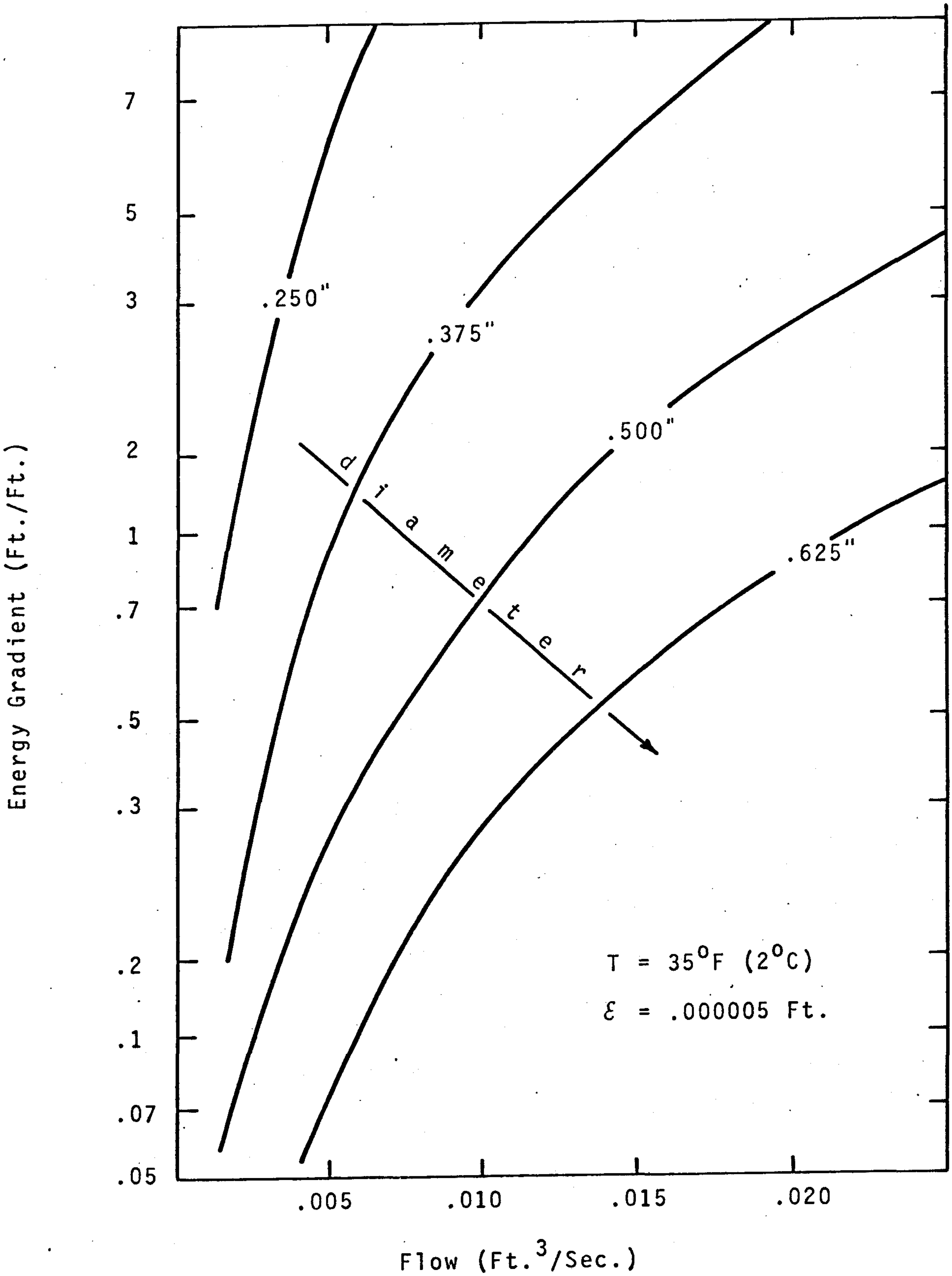
Program SYSOPT

- Sample Input Output Data Cont'd -

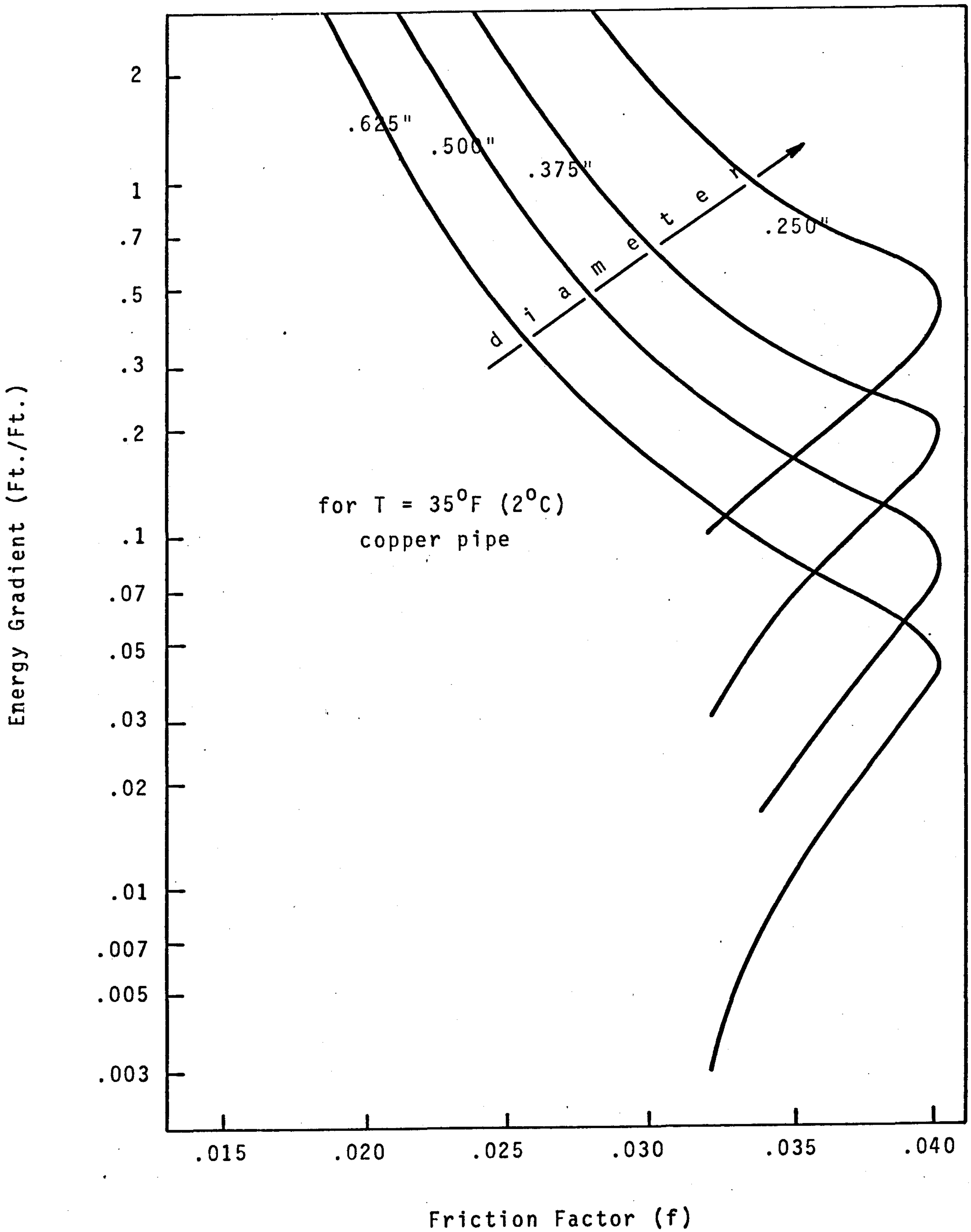
PUMPING HORSEPOWER	=	1.50
COST OF POWER TO PUMP	=	367.77
POWER LOAD OF PUMP	=	1.12
TOTAL INSULATION COST	=	20829.00
TOTAL HEATING TAPE COST	=	33975.00
TOTAL PIPE COST	=	15502.60
TOTAL CAPITAL COST	=	70306.60
ANNUAL COST OF CAPITAL	=	8981.22
ANNUAL COST OF POWER	=	10487.38
TOTAL ANNUAL COST	=	19468.60
TOTAL MAX. PWR. LOAD	=	43.78
TOTAL MAX. PUMPING LOAD	=	33.11

APPENDIX K

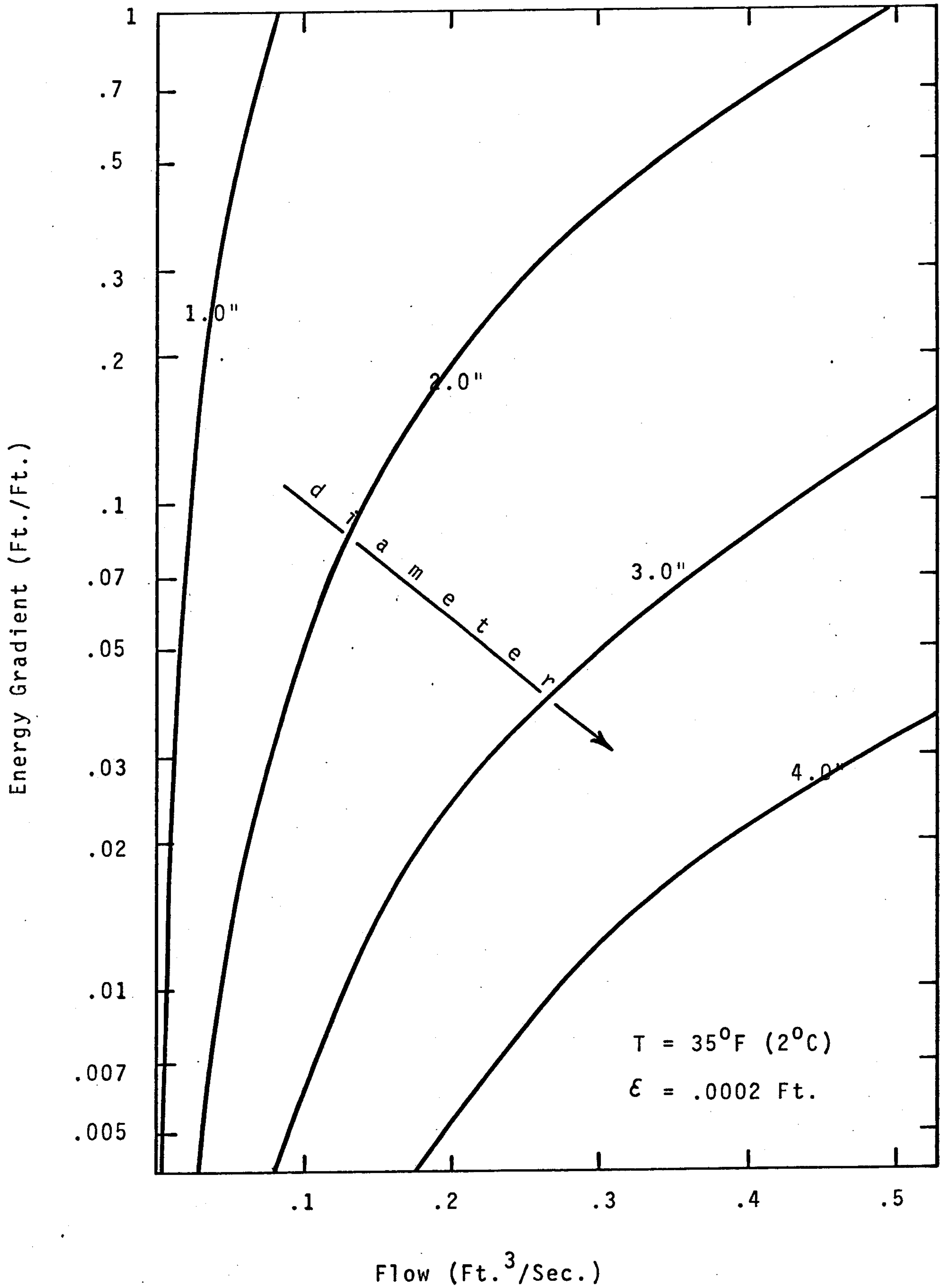
Flow in Copper Pipes



Friction Factor in Copper Pipes



Flow in Steel Pipes



Friction Factor in Steel Pipes