ESTIMATING FLOW TO AN INTERCEPTOR WELL

Design Project
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For Dr. Vijaya Raghavan
Design II
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PREAMBLE

Clean drinking water is a critical resource for the development and maintenance of human communities. Dry tropical and equatorial countries, especially those undergoing development and with limited monetary resources, often find the task of providing clean drinking water to the population prohibitively expensive. One solution is an interceptor well, which is a perforated pipe installed horizontally below the water table, most often to staunch unwanted flow down slope from the well. But design criteria for interceptor wells are not established. Thus a method is called for that would enable engineers to estimate the flow into an interceptor well before installation.

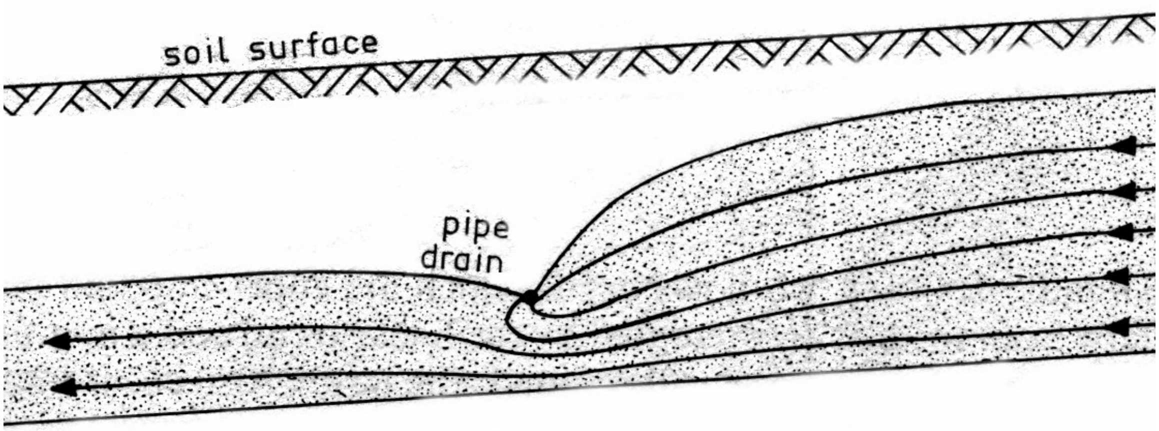

Figure 1. Cross-section through an interceptor drain. Reprinted from [1]

During the winter of 2002-2003 Groupe Consulteaux of Vaudreuil, Quebec designed and installed an interceptor well under contract for the Municipality of St. Clet to replace an older interceptor well already at the site. Since the older well was already providing water, extensive testing to determine potential ground water flow to the new well prior to installation was not necessary. Small diameter shallow test wells called piezometers were installed prior to construction of the new interceptor well to monitor water table height, measure aquifer material properties and allow water sampling for quality required by the *Règlement sur le captage des eaux souterraines* Q-2, r.1.3 of the province of Quebec. Gilles Bouclin and Marie-Josée Noiseux from Groupe Consulteaux began collecting water table data from the piezometers during the summer of 2003. This activity was continued sporadically until early November 2004. The goal was to record the flow of ground water into the well under varying water table conditions throughout the year. Bouclin and Noiseux hoped to analyze the data and apply the knowledge gained to estimate the flow at potential interceptor well sites in the future. This type of research is not normally possible for a small firm such as Groupe Consulteaux, thus data collection was not completed due to time and financial constraints. The author agreed to take on the project for Groupe Consulteaux as part of the ABEN 490 Design I and BREE 495 Design II courses taught by Dr. Vijaya Raghavan at Macdonald Campus, McGill University.

This report details the development of a method for estimating the flow of water to an interceptor well before installation, based on aquifer characteristics and the local topography. A formal problem statement along with objectives and the scope of the project is outlined. Research and testing of the method is presented, as well as the results of the testing and estimated accuracy. The final design is presented which includes protocols for the execution of each step of the process. A critique of the final design is followed by suggestions for improvement and further research.

1 PROBLEM STATEMENT

Design a method for estimating the water flow to an interceptor well prior to installation, in order to estimate the total amount of water available to the client.

2 OBJECTIVE AND SCOPE

The objective of the project is to develop a method for estimating the amount of water than can be harvested with an interceptor well, before installation. Critical factors to be considered in evaluating candidate methods are:

- Cost:
    - materials,
    - site preparation
    - total time required
- Accuracy
- Simplicity

The process of determining the expected flow will be inexpensive. The solution will require a minimum investment of time. The accuracy and precision of the method will also be important factors: if guessing the flow from the well based on experience or using more basic engineering approximations provides comparable solutions, investing a few more dollars in the new method will not be justifiable.

This project is not a complete overview of the design of an interceptor well, a process with which the engineers at Groupe Consulteaux are now very familiar. Instead the scope of the project lies within the preliminary stages of new-site development, when an unknown amount of flow to a planned interceptor well must be estimated in order to:

- Provide the client with an accurate estimate of water available for client's use
- Provide Groupe Consulteaux with an accurate estimate of flow for better design calculations
- Provide the government of Quebec with an accurate estimate of flow to meet the requirements set out in *Règlement sur le captage des eaux souterraines*

The success of the design will be determined by comparison of the expected flows calculated with the design method with the continuously measured volumetric flow rate recorded on a datalogger at the municipal pumphouse in St-Clet village, where a feeder pipe delivers water from the interceptor well, approximately three kilometers distant.

3 LITERATURE REVIEW

3.1 Horizontal Technologies for Harvesting Groundwater

The idea of using horizontal tunnels, or later, perforated pipes for the collection of groundwater is at least a thousand years old. In the medieval Middle East, Central Asia, and Northern India a host of technologies for gathering water was developed, including the *qanat* or *kariz*, a tunnel dug far into the side of a mountain to the water table. This tunnel would then be extended far out into the flatter arable or inhabited land, transporting water to the point of distribution. This technology was an improvement over open irrigation ditches because it prevented evaporation. [2] Two technologies similar to the *qanat* and using horizontal pipes are still in common use today: Infiltration galleries and interceptor drains. Infiltration galleries are perforated pipes which are jacked horizontally into a porous water-bearing geological formation from the bottom of a large concrete caisson. The pipes supply water to the caisson, where it is pumped upward to treatment and storage facilities. Interceptor drains are similar to infiltration galleries in function, yet they are generally installed very near the soil surface to drain away unwanted groundwater emerging along a line of seeps where an aquifer intersects the ground surface. Interceptor drains are the technology most similar to the interceptor well described in this report.

3.2 Calculating water flow in soils

In use today are three common methods for determining the flow of water in soils. The finite difference method is most commonly employed within a computer program because of the quantity of calculations involved. The aquifer is first divided into units of a regular rectangular shape called cells. Each cell is an indivisible unit of volume within the aquifer, and the relationship between each cell is regulated by equations derived from Darcy's Law to determine the flow over time through the simulated system. One of the early finite difference models, and one still commonly in use, is the MODFLOW model developed in the late 1970's and early 1980's by researchers at the United States Geological Survey. MODFLOW is in widespread use in North America and internationally, has benefitted from extensive testing and development by researchers both within the USGS and outside, and is also exhaustively documented to facilitate further development of add-on modules for specialized application of the model. [3] Although free, the time required to learn the MODFLOW software and build individual models precludes its use as a time-effective solution to the problem at hand.

Liquid flow through porous media can also be calculated analytically from first principles. Equations originally derived to describe the flow of thermal energy in solid media have been adapted to describe liquid flow through porous media. Such equations work best with very simple geometries, simple boundary conditions, and with relatively homogeneous aquifers. Under certain conditions these equations have been employed successfully.[4]

The method of flow nets is also widely used for the rapid determination of water flow through soil. The method of flow nets was developed by Paul Forchheimer and others in the early part of the 1900's based on work by the celebrated French engineer Henry Darcy. The earliest presentation of this method seems to be a paper written by him and published by the Austrian Academy of Sciences only a few decades after Darcy developed, by experimental means, his famous law: [5]

$$Q=-kA(h_1-h_0)/L \qquad (1)$$

where Q is the total discharge past a given cross-sectional area [L^3/T]
k is the saturated hydraulic conductivity in [L/T]
A is the cross-sectional area, orthogonal to the direction of bulk flow [L^2]
h_1-h_0 is the difference in hydraulic head between two points [L]
L is the distance between those points [L]

The method of flow nets employs flow lines parallel to the direction of flow and equipotential lines perpendicular to the direction of flow to divide the saturated zone around the feature of interest into cells with roughly equal flow and equipotential boundary lengths. Two flow lines define a flow channel.

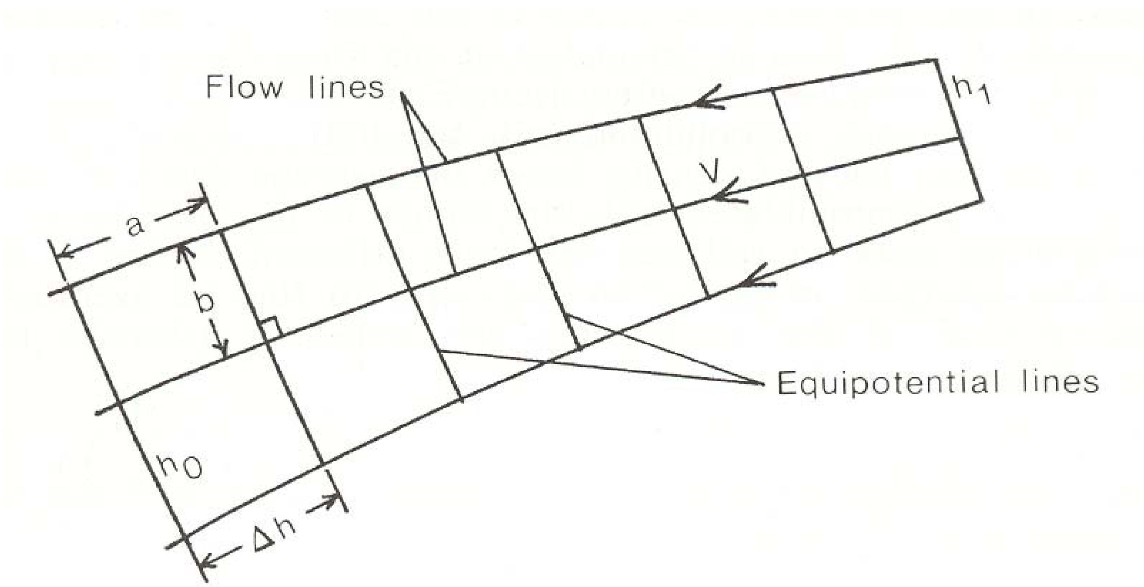

Figure 2. Sample construction of a flow net. Diagram reprinted from [6]

The rate of water flow through one flow channel is:

$$q=dV/dt=vb=k\Delta hb/a \qquad (2)$$

where q is the rate of water flow per unit length [L^2/T]

dV/dt is the volume of water flowing past a cross-section per unit time
v is the velocity of flow of water [L/T]
k is the saturated hydraulic conductivity in the a direction [L/T]
Δh is the drop in hydraulic head across one cell [L]

If it is assumed that all cell dimensions b are equal to all corresponding cell dimensions a such that every cell in the flow net is a square, every drop in potential along the flow path is equal to $(h_1-h_0)/n_d$. If flow lines are drawn such that the distance b between each flow line splits the total cross section of flow into exactly n_f flow paths, the volume of flow per unit time per unit width is

$$q=k(h_1-h_0)n_f/n_d \qquad (3)$$

The seepage per unit width can be easily computed with the above equation once a flow net has been constructed. The flow net is drawn so that every boundary to flow is a flow line. The distance between any two boundaries is split evenly into the desired number of flow paths n_f to give good resolution of the flow path. Equipotential lines are drawn perpendicular to all flow lines and spaced so that the average width of each flow path within a cell is equal to the average distance between equipotential lines outlining that cell. [5,6] Drs. Broughton and McKyes in the Department of Bioresource Engineering at McGill University both report that the method of flow nets is by far the easiest and most common way to calculate flow through soil. [7,8]

Analytically the flow to an interceptor well is very similar to the flow to agricultural tile drains. Hooghoudt's Equation for the spacing between parallel drains in a field was originally developed in Holland and published in 1940 based on simplifications to the method of flow nets. Hooghoudt realized that flow to drains was similar to flow to parallel open ditches, except very close to the drains where flow is radial. Although specialized application of Hooghoudt's Equation has been used to great effect, assumptions of Hooghoudt's Equation will not hold for the case presented here. Since Hooghoudt's Equation is based on the method of flow nets, better accuracy should be attainable with careful application of the flow net method. The method of flow nets is uniquely suited to the solution of localized water flow problems, and is easy to implement. [6]

4 SOLVING THE PROBLEM

4.1 Candidate Methods for Solving the Problem

Three methods were under consideration for solving the problem of estimating the flow through a porous medium to an interceptor drain:

- A finite difference software package such as MODFLOW
- Analytical methods
- The method of flow nets

All three were researched and considered. Factors in the decision-making process were the cost, time required, and input from professionals in the field. The method of flow nets appeared to be the easiest and fastest approach, and was recommended by professionals in the field of soil mechanics.

4.2 Input Data Needed

Data needed in order to test the method of flow nets:

- Several sets of water table heights measured in the piezometers currently on the site
- The corresponding steady-state flows measured in the St. Clet pump house on or near the same day as measurements were taken at the site
- The saturated hydraulic conductivity for as many locations and depths around the site as possible

5 TESTING

5.1 Objective

The objective of testing is to establish the accuracy of the method of flow nets using the St. Clet site.

5.2 Method of Testing

5.2.1 Site Plan

The St. Clet interceptor well designed by Group Consulteaux is ideal for testing the method of flow nets. The interceptor well is a 600 meter long permeable drain pipe. An impermeable geotextile has been laid above the pipe to prevent surface contaminants from percolating directly to the well. 14 piezometers made of PVC conduit have been drilled down to the depth of the water table in the area surrounding the interceptor well. The piezometers are located in three transects through the water table cross-section from approximately 50 meters uphill of the interceptor well to a distance of about 20 meters below the interceptor well. These transects enable the engineer to model the topography of the water table in the vicinity of the interceptor well. A feeder pipe near the middle of the interceptor well collects water and delivers it down slope to a sand trap. An overflow is installed at the sand trap to drain excess water when the Municipality has enough in storage. From the sand trap a 3 km conduit brings the water by gravity flow into the pump house in St. Clet village, where water is fed to a tank through a pair of float-controlled valves. The flow through these valves, the height of water in the tank, the municipal water demand, and several chemical indicators are registered in real time by a data logger installed in the St. Clet pump house. Software provided with the data logger enables graphical representation of the data. For an overview of the interceptor well as-built, please see Appendix A: Site plan and interceptor well cross-section.

5.2.2 Hydrogeologic Context

The deposits that make up the hydrostratigraphic units at the St. Clet site are of glacio-marine origin. The fine sediment fraction, composed of clay and silt, was deposited in deep, calm water at the end of the last ice age after the glaciers retreated. The larger sediments such as sand and gravels originate from terraces formed by wave action at the edge of the Champlain Sea out of glacial deposits. Sand and gravels from these terraces are easily distinguished from sand and gravels directly deposited by glaciers due to their stratification and uniformity within layers, since direct glacial deposition is mixed and unsorted. [9]

Hydrogeologist Donat Bilodeau, under subcontract for Groupe Consulteaux, carried out hydrostratigraphic analysis at the site between November 2001 and January 2002. Two main hydrostratigraphic units make up the local hydrogeology:

- *Fine sand from marine terraces*: Fine stratified sand. Particle size varies with depth. This unit constitutes the aquifer that supplies the interceptor well with water.

- *Marine silt clay*: Composed of silt, gray clay, and approximately 30% coarser material such as fine sand and in one location gravel. This unit is an aquiclude, preventing water from percolating deeper underground. This unit comes close to the surface of the ground at the terrace, causing the water table to intersect the surface.

The sand unit extends from the surface to a depth of between 7 and 12 meters. Below this depth, alternating layers of marine silt clay and fine sand extend deeper. These subsurface layers contain ground water but are only weakly connected with the superficial aquifer due to the relative hydraulic impermeability of the silt clay layers. [9]

5.2.3 Experimental Method

In order to test the method of flow nets at this site, all water table heights were measured in the piezometers over the course of one year. The complete data table for the piezometers is included in Appendix B: Water table log from piezometers at St. Clet. Assumptions for the method of flow nets were:

- All flow is orthogonal to the long axis of the interceptor well
- The saturated hydraulic conductivity is isotropic within a transect
- Constant conditions exist on both sides of each transect from the midpoint between that transect and its neighbor. End transects represent conditions from the end of the interceptor well on one end to the midpoint between that transect and the next transect toward the center. For the three transects at the site there are consequently three zones where conditions are assumed to be constant and represented by the transect.
- Flow is at steady-state for the period depicted by the flow nets. Thus, the phreatic line forming the upper boundary of the flow net is a flow line, and water enters the flow net from the aquifer source only.

For a graphical explanation of these assumptions, the locations of all piezometers and transects, and zones considered to have constant conditions, please see Appendix C: Piezometer placement, as well as Appendix F: Example of flow net construction from St. Clet, for the shape of the flow nets in the three transects.

The accuracy of saturated hydraulic conductivity data for the study site is questionable, and may affect the accuracy of the final outcome of the tests. The piezometers on site were not installed according to the standard *CAN/BNQ 2501-135 Sols-Détermination de la Perméabilité-Type Lefranc,* such that they cannot be used to determine the hydraulic conductivity of the soil at the site using the method set out in the standard. As well, the water depth in the piezometers is on average too low to use the rising water level method, and the piezometers are generally too far into the woods to use the method of constant water level, which requires a pump, a very accurate flowmeter and a large supply of water. The rising water level method was conducted by the author on four piezometers at the site, with poor results due to low initial water table, unknown area of infiltration, and too-rapid rise in water table height after drawdown (approximately 10 cm/s). See [10] for an explanation of these methods of estimating saturated hydraulic conductivity. Granulometric analyses were performed on soil samples from piezometers installation, and these analyses were used to estimate the saturated hydraulic conductivity by an empirical formula developed by Hazen. [11] According to Dr. Edward McKyes, however, the Hazen method based on granulometric analysis is not an accurate determination of saturated hydraulic conductivity. [8] The saturated hydraulic conductivity for each transect and zone was approximated as the average saturated hydraulic conductivity in all boreholes using the Hazen method as reported in *Document d'Appel d'Offres. Ouvrages de captage d'eau souterraine. Chapitre H: Rapport Hydrogeologique* [9].

The elevation of the impermeable clay layer was assumed to be constant under the entire interceptor well at the elevation of 93.85 found in the F-8 bore hole, even though the results of drilling indicated that it varied by at least 0.62 meters among the three holes in which the drill went deep enough to find a clay layer. The elevation of the clay layer at each location is shown in the table below.

Bore hole	Elevation of clay layer [m]
F-9	94.12
F-8	93.85
F-7	93.49

Table 1.

The flow per meter length of well was calculated for each zone and multiplied by the length of well pipe within the zone to get the total expected flow in each zone. These flows were added together to obtain the total expected flow from the interceptor well. These modeled values were compared to the flow values obtained from the data logger at the St. Clet pump house. The pump house is the final destination of all water collected in the interceptor. It is assumed that the steady-state inflow to the pump house is the same as the outflow from the interceptor well. This conduit was pressure-tested by Groupe Consulteaux before construction began on the new interceptor well. The conduit was also inspected by remote camera as well. Both tests found the conduit to be without leaks. [13]

The inflow at the pump house must be equal to the flow out of the interceptor well at the site in order to compare expected values obtained with the method of flow nets to real-world flows. This is not always the case. There is limited capacity for water storage in the tank under the pump house, thus in periods of low water demand the two float valves which allow water from the interceptor well into the tank are closed. During this time, water will back up through the pipes to the interceptor well and overflow at the sand trap located to the southwest of the well. When the valves are again opened under high water demand, there is a period of unsteady flow as the accumulated water inside the 3 km conduit drains out and the flow at the pump house goes to steady state. When both valves are open for a significant period, the graphs of flow versus time obtained using the data logger software for the two valves that feed the pump house attain a slope of 0. In this way, the flow into the interceptor well is approximated by the combined flows into the St. Clet pump house at steady state, although the flow is not always under this condition. For an example of both the non-steady-state and steady-state flows as measured at the St. Clet pump house please see Appendix D: Sample data logger output.

5.3 Test results and discussion

The flow from the interceptor well is not highly variable. For the period of flow measurement May 2003 to July 2005, the maxima and minima measured at the St. Clet pump house are 12.6 liters/second and 10.0 liters/second, respectively, a difference of only 20%. Week-to-week flows tended to change only gradually, justifying water table measurement at periods of one week or more.

Graph showing flow into the St. Clet pump house versus time

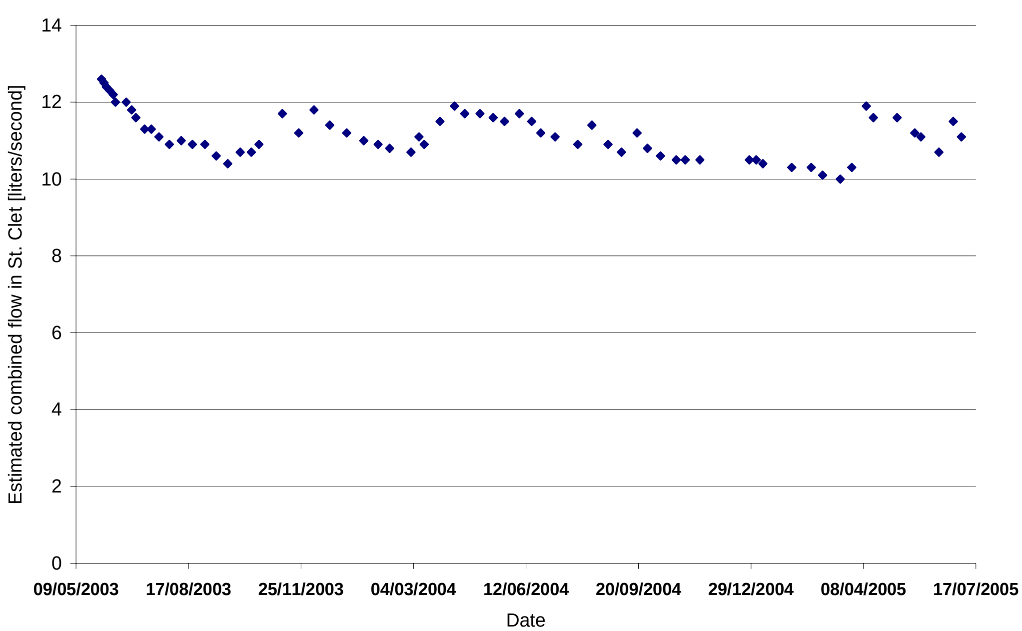

Figure 3.

Preliminary calculations using older data from the site indicated that the water table height was well correlated with flow from the interceptor well measured in St. Clet. A simple linear regression was performed in November 2003 on the average depth to water table measured at the site since the summer of 2003 versus the steady-state flow of water from the St. Clet pump house for corresponding days. The results showed a linear relationship with an R^2 of 0.88 for the measured range of values.

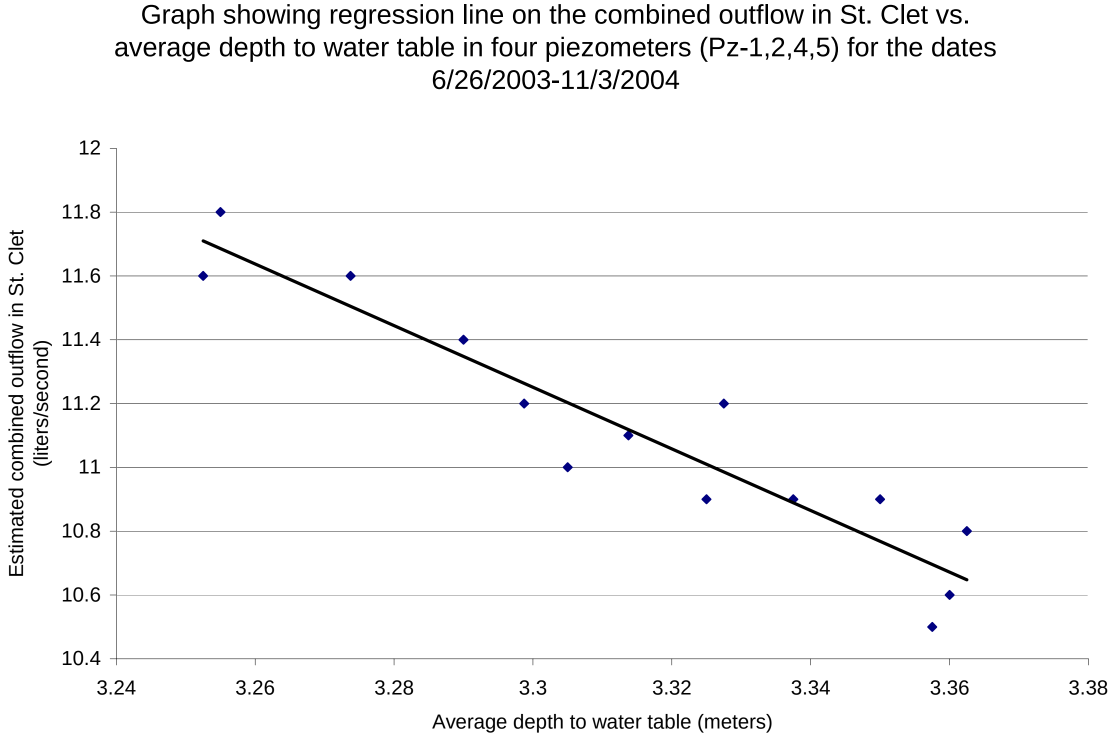

Figure 4.

These preliminary results indicated a linear relationship between the height of the water table in the vicinity of the interceptor well and the outflow from the well. This implied that modeling the relationship can provide good predictability if the model accuracy is high.

Results of testing the method of flow nets show that modeled flows to the interceptor well were within an order of magnitude of the expected flows measured at the St. Clet pump house. Modeled flows were approximately 2.5 times greater than expected values. The maximum modeled flow of 25.4 liters per second corresponds to the maximum measured flow of 10.7 liters per second. The minimum modeled flow of 24.7 liters per second corresponds to two values of minimum measured flow at 10.5 liters per second.

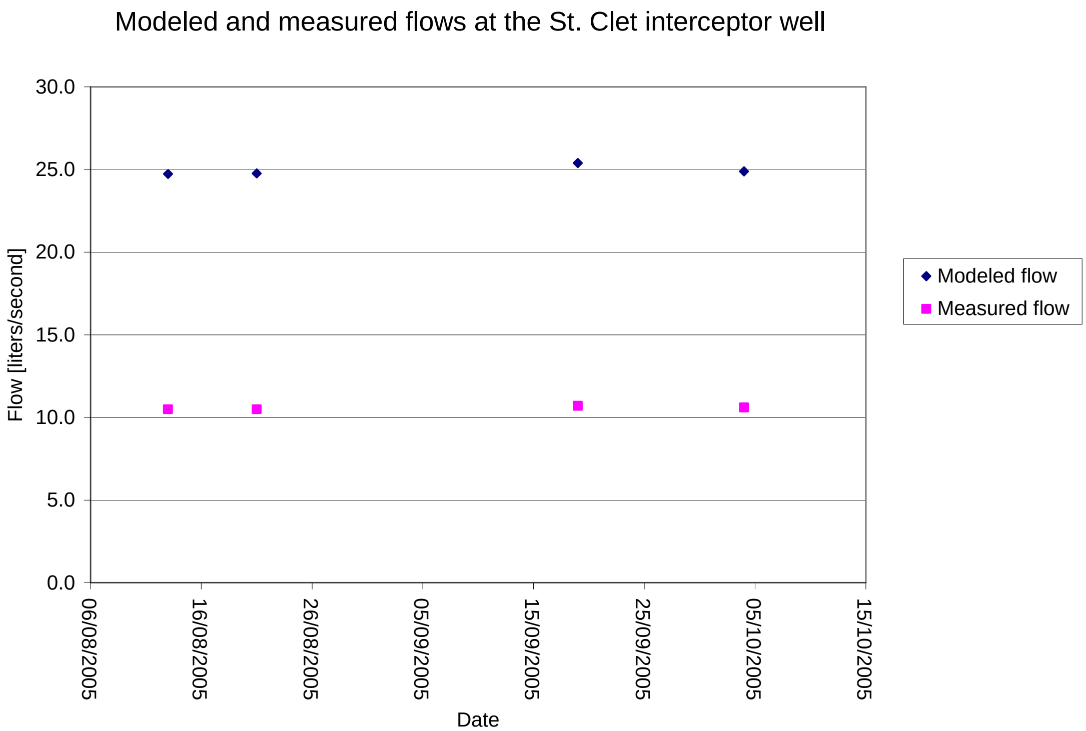

Figure 5.

Date	$Q_{modeled}$	$Q_{measured}$
13/08/2005	24.7	10.5
21/08/2005	24.8	10.5
19/09/2005	25.4	10.7
04/10/2005	24.9	10.6

Table 2.

A linear regression on the modeled flow versus measured flow indicated that flows are well-correlated, with an R^2 value of 0.9105 for four data points. This value would likely improve if the flowmeter at the St. Clet pump house was precise and accurate to two decimal places.

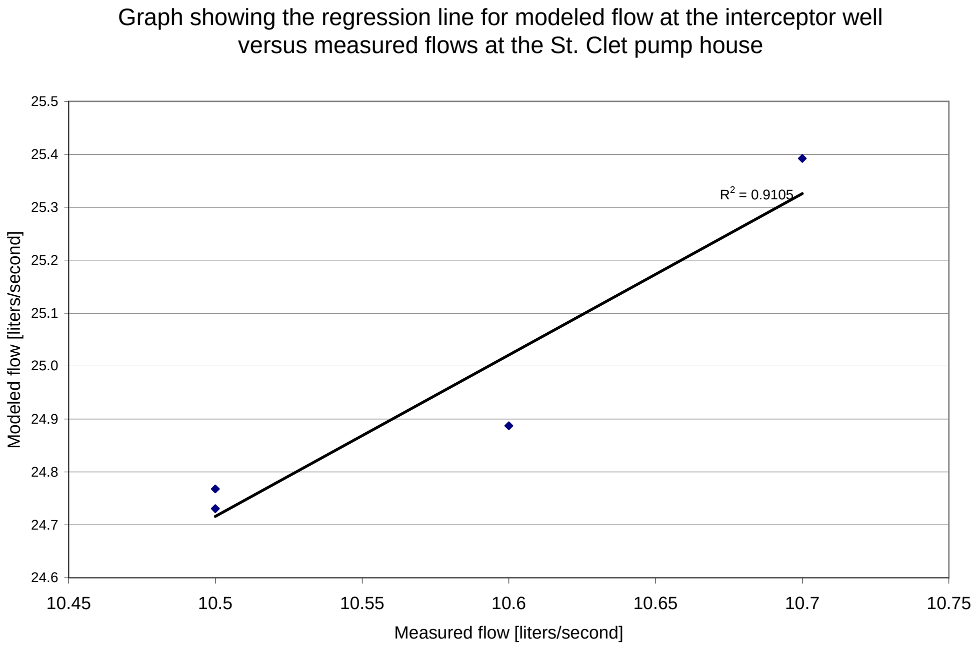

Figure 6.

The results were quite accurate considering the assumption of constant saturated hydraulic conductivity over the entire site. This is especially true considering the large range of saturated hydraulic conductivities for sandy soils. [6] The results from flow net calculations suggest that the method of flow nets can be an accurate method for modeling the flow into an interceptor well if the flow nets are drawn with precision and the saturated hydraulic conductivity parameter is accurately measured.

The assumption of zero recharge from the ground surface to the aquifer simplifies the construction of flow nets but may not be accurate. During periods of little or no precipitation, when soil moisture conditions are drier, the assumption is tenable. This is especially true for sandy or gravelly soils of high saturated hydraulic conductivity which drain easily, such as beach sand. The terrace on which the interceptor well is situated was once a beach on the border of the Champlain Sea, however there are significant silt lenses within several profiles that would increase the hydraulic conductivity by at least 10^1 m/s. This assumption of zero recharge will be entirely inaccurate for other soil types, except under the driest soil moisture conditions. The error introduced by assuming zero recharge under varying soil moisture conditions in constructing flow nets at this site is not known.

Assuming constant saturated hydraulic conductivity over the volume of aquifer feeding the interceptor well is also an inaccurate assumption, but necessary under the circumstances:

- The water level in the piezometers was too low to perform a rising water level pumping test. A minimum depth of water of 1 meter is recommended, while the water depths in four piezometers at the time of testing averaged 0.2 meters.

- The height of perforations in the piezometer material was not known, thus the area infiltrating water during a falling water level pumping test would be unknown.
- A high-volume pump, water tank, and accurate flowmeter are needed for a constant-level pumping test.

The best practice in the future for finding saturated hydraulic conductivity will be to add more piezometer transects at the site, and measure saturated hydraulic conductivity in each piezometer by one of the pumping tests.

Though not entirely conclusive due to the small number of data points, the regression analysis on the modeled and measured flows indicates that by adjusting one or more parameters the modeled flows can be brought in line with the measured flows.

6 PROTOCOL FOR ESTIMATING FLOW TO AN INTERCEPTOR WELL

Following is the complete protocol for estimating the flow to an interceptor well before the well has been installed.

6.1 Installing piezometers

Piezometers must be located in transects which are parallel to the direction of flow, and perpendicular to the planned axis of the interceptor well. Each transect should be composed of a minimum of four piezometers, with the following approximate locations. Please see Appendix C for example piezometer placement from the St. Clet site.

- 1 piezometer in each transect should be drilled at least 50 meters uphill and ideally 100 meters or more uphill from the planned location of the interceptor well. Hydrogeologist Donat Bilodeau estimated the zone of influence of the interceptor well at St. Clet to be between 30 and 100 meters. [8] The zone of influence is the area around a well where the water table height is measurably affected by drawdown in the well. The further away from the interceptor well the first piezometer is placed, the more accurate the flow net calculations will be.

- 1 piezometer in each transect should be located 25-33% of the horizontal distance between the planned interceptor well and the furthest piezometer uphill. Although data from this piezometer will not be used in the initial flow net calculation, it will be an essential data point for constructing flow nets for further research after installation. Under flow to the interceptor well, the rate of change of the slope of the water table in this region is very high, therefore it is useful in drawing the flow net to have a known water table height in this region.

- 1 piezometer in each transect should be located at or within a few meters of the planned location of the interceptor well. The primary function of this piezometer is to measure the saturated hydraulic conductivity of the soil in the near vicinity of the planned well. The bottom of the piezometer should be located at the planned elevation of the interceptor well pipe.

- 1 final piezometer should be located 5 to 25 meters downhill from the planned location of the interceptor well.

The accuracy of the results of flow net calculations will be proportional to the number of transects included in the analysis. The ideal distance between transects will be a function of the variability of soil properties and topography and the marginal cost of including another transect in the analysis. From the results of the test of the method of flow nets at the St. Clet site, it is clear that the value chosen for the saturated hydraulic conductivity in each zone is an important parameter for the final result. This decision is left to the discretion of the engineer, although care is recommended in choosing a suitable average saturated hydraulic conductivity.

Piezometers should be installed in accordance with the standard CAN/BNQ 2501-135 *Sols-Détermination de la Perméabilité-Type Lefranc*. [10] *It is very important for the measurement of saturated hydraulic conductivity that piezometers be installed according to the standard set forth in CAN/BNQ 2501-135.* A diagram summarizing the process is included in Appendix D: Piezometer installation.

When the piezometers are installed, soil samples should be taken in each stratum encountered. A granulometric analysis should be performed on all samples, and the hydraulic conductivity should be calculated using the Hazen method or other accepted method of estimating hydraulic conductivity based on granulometric analysis. Granulometric analysis will be required by the Ministry of Environment as part of the permitting process as well.

6.2 Measuring water table height

Water table height should be measured in every piezometer at intervals of one week or longer, but not in shorter intervals. A two-week interval is generally sufficient based on the flow regime at St. Clet, when there has not been a significant precipitation or snowmelt event. Four to eight collection days over a period of one to two months will be sufficient for an initial estimation of flow to be provided to the client. Obviously, one entire year of data collection is needed to find annual variation in the flow. This length of study period will not be generally feasible, however.

The water table height is measured at each piezometer from the highest point on the piezometer down to the surface of the water table. A portable electric water level meter is the best tool for measuring. Each measurement should be recorded to the nearest centimeter.

6.3 Measuring saturated hydraulic conductivity

Saturated hydraulic conductivity is calculated based on one of the pumping tests outlined in CAN/BNQ 2501-135 *Sols-Détermination de la Perméabilité-Type Lefranc.* Saturated hydraulic conductivity for each transect and zone can be considered isotropic, unless even greater accuracy is required. For increased accuracy it may be assumed that different layers have differing saturated hydraulic conductivities, although assuming heterotropic saturated hydraulic conductivity will lead to much more complex flow nets. If this level of accuracy is desired, the literature should be consulted for advanced flow net construction guidelines.

The depth to the impermeable layer must be measured as well. At least one auger hole should be drilled to the impermeable layer for each transect.

6.4 Estimating the flow into the interceptor well using flow nets

Construct a profile view of the piezometers, the proposed interceptor well pipe, the impermeable layer, and the water table height in the highest and lowest piezometers in each transect. Construct one profile view per transect. Although the surface of the water table may be assumed to be a parabolic free surface as derived by Dupuit, [7] only two water table elevations will be known in each transect, as the water table height measured by the two piezometers closest to the interceptor well will change drastically once the interceptor well has been installed. Without data points between the intended elevation of the bottom of the interceptor well pipe and the uppermost and lowermost piezometers, the most accurate representation of the water table is a straight line connecting each of these points with the bottom of the interceptor well pipe. If particularly high flows are expected, or if after modeling it is found that the interceptor well will flow at half-full or greater then the intersection between the water table and the interceptor well pipe should be adjusted to reflect this.

Because of the high saturated hydraulic conductivity of the backfill material relative to the surrounding soil, the saturated area below the water table and within the backfilled trench should be assumed to be at the same hydraulic potential as the bottom of the interceptor drain pipe. No equipotential lines should be drawn within the backfilled area around the pipe.

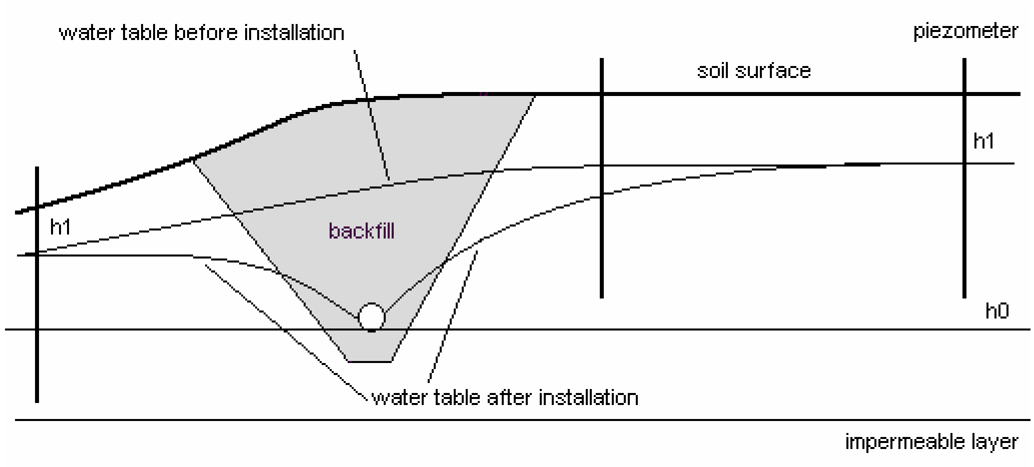

Figure 7. Water table before and after installing interceptor well pipe.

Since it is assumed that there is no recharge from above and the only source of flow is from the aquifer uphill, the upper surface of the impermeable layer acts as a flow line. At a point directly below the well pipe, the flow is vertical upward from the impermeable layer toward the pipe. Between these lines draw a third line midway between the upper and lower flow line that intersects the well pipe radially. Finally, draw equipotential lines. Starting at the farthest point from the well pipe, draw lines that are perpendicular to each flow line, and that create squares between the flow lines such that the average height and width of each square is the same. The distance between each equipotential line is determined by the mean distance between the flow lines. Please see Appendix F: Example of flow net construction from St. Clet.

After the flow net has been constructed, use the flow net equation from (3) for flow per meter length of the well pipe:

$$q=k(h_1-h_0)n_f/n_d \qquad (3)$$

where q is the volumetric flow per meter length of well pipe, for the transect and zone of interest
k is the saturated hydraulic conductivity for the zone of interest
h_1-h_0 is the height difference between the water table at the piezometer farthest uphill from the interceptor well and the midpoint of the cross section of the interceptor well.
n_f is the number of flow paths
n_d is the number of drops in hydraulic head along the flow path. Count the number of squares drawn in one flow path from the beginning of the flow path to the interceptor well pipe.

This calculation should be repeated for the flow on the low side of the interceptor well. When the flow per meter length has been calculated for each transect, the flow should be multiplied by the width of the zone around each transect.

$$Q_{zone\ i}=q_{transect\ i}*width_{transect\ i} \qquad (6)$$

These values are then added to get the total flow into the interceptor well for the measured water table levels. A sample spreadsheet of flow net calculations based on the above equations is included in Appendix G: Sample spreadsheet for flow net calculations.

7 RECOMMENDATIONS FOR FUTURE WORK

Much work could be done to improve the accuracy of this model. This study indicates that further work would be rewarded with much-improved model performance. The following are suggestions for accomplishing this:

- Continue to measure the water table height in the piezometers at the site. Only four days of samples were acquired that were sufficiently complete to be used for modeling.
- Practice and improve the technique of constructing flow nets. Seek advice from Drs. McKyes and Broughton at Macdonald Campus of McGill University. The technique takes time and experience to perform accurately.
- Measure the saturated hydraulic conductivity more carefully, with one of the other methods available. New auger holes will need to be dug. Drill several more auger holes per zone, and find a method to calculate the average saturated hydraulic conductivity. Perform all flow net calculations again with the new values.
- Establish a method of calculating the proper piezometer spacing, or establish a general rule of thumb to be used for this purpose. This will require experience from other interceptor wells.
- Economic considerations always determine the final design. If directly measuring the saturated hydraulic conductivity in each piezometer at the site is too expensive and time-consuming, a better method for estimating this parameter based on granulometric analysis will be required. Several other methods are currently available. [11] These should be used in future projects and tested for accuracy.

CONCLUSION

Clean drinking water is a resource vital to all human communities, but can be expensive to provide. Interceptor well technology is a cheap, low-maintenance solution to the problem of supplying clean drinking water to a community. Groupe Consulteaux installed an interceptor well for the Municipality of St. Clet in 2003 to replace an aging water collector on-site, without conducting in-depth analysis of the potential flow from the well. The author agreed to conduct research at the site and design a protocol for estimating the flow from a planned interceptor well. The final design consisted of piezometer transects to measure the water table height and saturated hydraulic conductivity and utilization of the method of flow nets to estimate the flow into the interceptor well. Results of modeling with flow nets are consistently 2.5 times higher than measured values, although the modeled and measured values are strongly correlated. Test results suggest that the saturated hydraulic conductivity, averaged over the whole study area, did not accurately reflect the soil properties at the site. The strong correlation suggests that improving the flow net construction and measuring saturated hydraulic conductivity accurately and locally within zones would significantly improve the performance of this model. Saturated hydraulic conductivity should be measured by one of the other methods available, and values should be chosen that reflect the average value within each zone. Further water table measurements should be taken in the piezometers at the site and flow net calculations updated to improve accuracy and increase the database.

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APPENDIX A: Site plan

APPENDIX B: Water table log for piezometers at St. Clet

Piezometer	19/11/01	27/11/01	08/01/02	06/03/02	28/03/02	21/05/02	30/05/02	04/07/02	09/08/02	19/08/02	17/04/03	26/06/03	03/07/03
F-2	1.22	1.21	1.20	1.20	1.20	1.18	1.16	1.22	1.25	1.26		1.73	1.72
F-7	0.60	0.58	0.57	0.57	0.57	0.57	0.55	0.62	0.65	0.67		1.10	1.95
F-10	0.66	0.63	0.60	0.63	0.59	0.55	0.54	0.57	0.63	0.64		1.67	1.71
F-11		4.98		4.78	4.73	4.62	4.67	4.71	5.11	5.21		4.19	4.39
F-12		1.46		1.31	1.27	1.17	1.22	1.26	1.67	1.78		1.43	1.57
Pz-1												2.06	2.07
Pz-2											2.94	3.13	3.15
Pz-3												2.67	2.71
Pz-4												3.23	3.27
Pz-5												4.60	4.61
Pz-6												5.29	5.32
Pz-7												4.42	4.39
Pz-8												4.80	4.83
R-0												3.22	3.26
R-1													
R-2													4.63
R-3													4.99
R-ouest												> 5,08	> 5,08
R-est												5.20	> 5,28
Pz-9													
Pz-10													
Pz-11													
Pz-12													
Pz-13													
Pz-14													

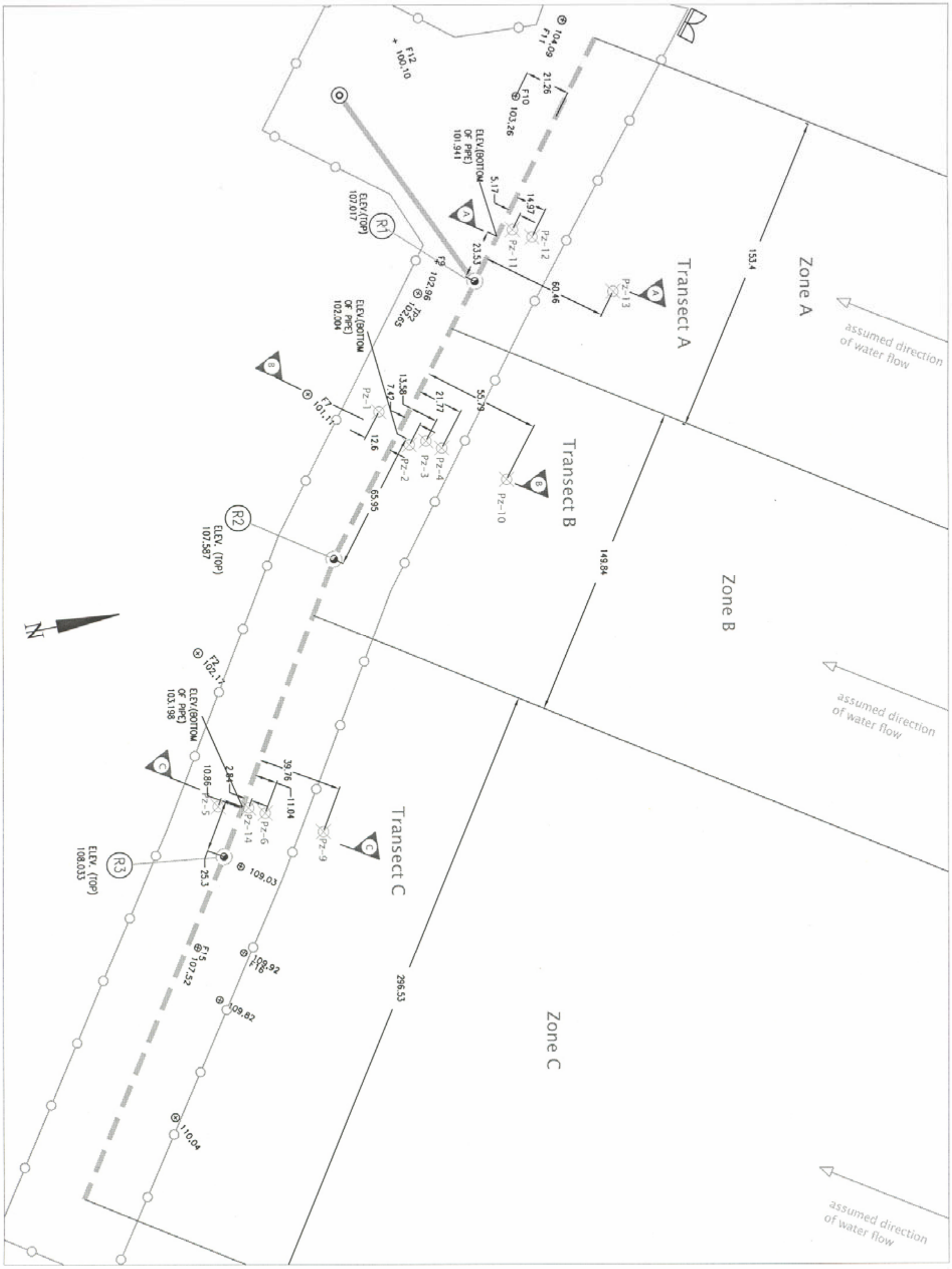
Piezometer	08/07/03	16/07/03	23/07/03	30/07/03	11/08/03	21/08/03	13/09/03	15/01/04	08/03/04	29/04/04	30/08/04	16/09/04	30/09/04
F-2		1.71	1.72	1.74	1.69	1.77		1.67	1.96	1.59		1.75	1.74
F-7		1.08	1.05	1.08	0.99	1.14		1.00	0.95	0.95		1.05	1.09
F-10	1.75	1.72	1.70	1.72	1.64	1.77	1.80		0.96	1.56		1.67	1.75
F-11		4.18	4.14	4.05	3.85	3.79		3.15	3.06	3.01			
F-12		1.72	1.74	1.74	1.65	1.74	1.88	1.27	1.25	1.12		1.48	1.52
Pz-1	2.10	2.08	2.08	2.10	2.04	2.11	2.12	2.30	2.82	1.96	2.12	2.06	2.10
Pz-2	3.16	3.18	3.21	3.20	3.22	3.23	3.26	3.22	3.25	3.18	3.28	3.24	3.28
Pz-3	> 2,72	> 2,72	> 2,72	> 2,72	> 2,72	> 2,72	3.43	3.35	3.37	3.31	3.46	3.43	sec
Pz-4	3.29	3.32	3.35	3.37	3.34	3.38	3.42	3.33	3.36	3.27	3.37	3.40	3.45
Pz-5	4.61	4.62	4.62	4.63	4.62	4.63	4.63	4.62	4.60	4.60	4.63	4.61	4.62
Pz-6	5.32	5.34	5.35	5.37	5.38	5.39	5.42	5.36	5.36	5.27	sec	5.32	5.40
Pz-7	4.42	>4,42	>4,42	>4,42	>4,42	>4,42	>4,42	>4,42	>4,42	>4,42	sec	4.42	sec
Pz-8	4.86	4.89	4.92	4.95	4.98	5.00	5.05	4.96	>6	4.77	sec	5.03	5.05
R-0													
R-1													
R-2													
R-3													
R-ouest	5.08												
R-est	5.28												
Pz-9													
Pz-10													
Pz-11													
Pz-12													
Pz-13													
Pz-14													

APPENDIX B: Water table log for piezometers at St. Clet continued

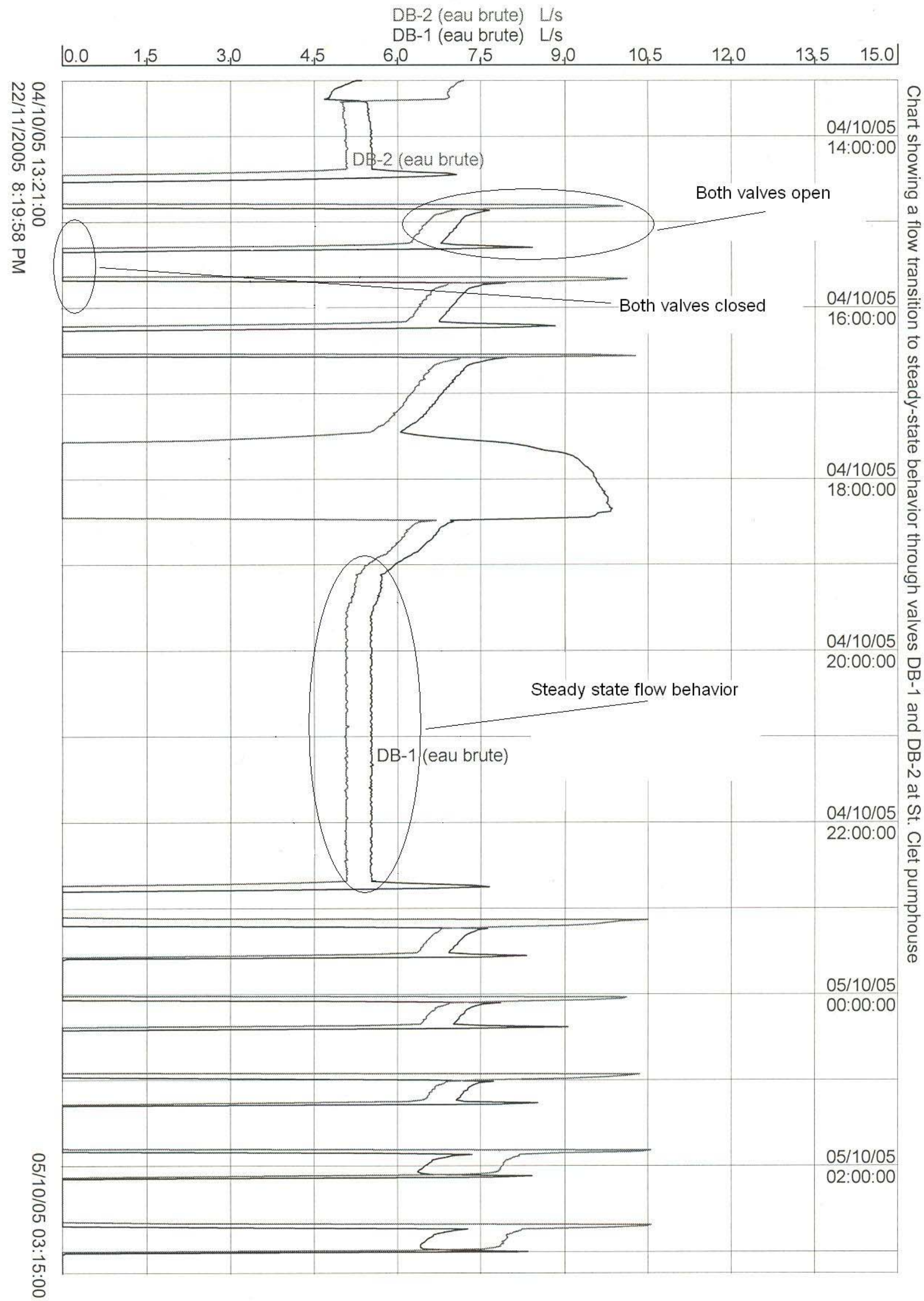
Piezometer	03/11/04	10/11/04	24/11/04	08/12/04	15/12/04	30/01/05	06/02/05	13/03/05	20/03/05	27/03/05	09/04/05	24/04/05	28/04/05
F-2	1.69	1.70	1.60	1.65	1.70	1.69					1.59		
F-7	0.99	0.98	0.97	0.97	1.01	1.00		1.70			0.93		
F-10	1.66	1.69	1.65	1.64	1.79	1.69		1.69			1.55		
F-11	3.46	3.48	3.34	3.25	3.35	3.55		3.39			3.20	3.12	
F-12	1.47	1.48	1.45	1.35	1.38	1.43		1.45			1.45		
Pz-1	2.05	2.06	2.03	2.01	2.04	2.04	2.04	2.04	2.04	1.93			
Pz-2	3.30	sec	3.26	3.25		3.26	3.27	3.28	3.28	3.28	3.18		
Pz-3	sec	3.47	3.48	3.45	3.46	3.47	3.49	3.51	3.51	3.51	3.35		
Pz-4	3.47	3.43	3.45	3.43	3.43	3.47	3.48	3.50	3.50	3.49	3.30		
Pz-5	4.62	4.59	4.61	4.62	4.63	4.62	4.62	4.62	4.62	4.62	4.54		
Pz-6	5.41	5.40	5.42	5.42	5.43	5.43	5.44	5.44	5.45	5.45	5.33		
Pz-7	sec	sec	sec	sec	sec	sec	sec	sec	sec	sec	sec		
Pz-8	5.09	sec	sec	5.12		5.13	5.13	5.15	5.15	5.16	4.96	4.93	
R-0													
R-1													
R-2													
R-3													
R-ouest													
R-est													
Pz-9								4.47	4.46	4.47	4.28	4.27	4.27
Pz-10								3.72	3.72	3.72	3.42	3.5	
Pz-11											4.06		
Pz-12											4.33		
Pz-13											4.25	4.21	
Pz-14													

Piezometer	16/07/05	13/08/05	21/08/05	19/09/05	04/10/05
F-2		1.82		1.71	1.76
F-7		1.12	1.06	1.00	1.06
F-10		1.80	1.76	1.64	1.71
F-11		4.26	4.27	4.27	4.10
F-12		1.86	1.89	1.63	1.59
Pz-1	2.11	2.11	2.11	2.04	2.07
Pz-2	3.26	3.26	3.26	3.26	3.26
Pz-3	3.47	3.50	3.51	3.49	3.50
Pz-4	3.43	3.47	3.47	3.47	3.47
Pz-5	4.67	4.62	4.62	4.61	4.61
Pz-6	5.37		5.40	5.41	5.42
Pz-7					
Pz-8	4.99	5.05		5.09	
R-0					
R-1					
R-2					
R-3					
R-ouest					
R-est					
Pz-9	4.3	4.35	4.36	4.38	4.4
Pz-10	3.51	3.57	3.57	3.58	3.62
Pz-11	4.1	4.13	4.13	4.13	4.13
Pz-12	4.37	4.41	4.41	4.42	4.42
Pz-13	4.14	4.21	4.23	4.26	4.29
Pz-14	4.58	4.59	4.59	4.59	4.6

APPENDIX C: Piezometer placement



APPENDIX D: Sample data logger output



APPENDIX E: Piezometer installation

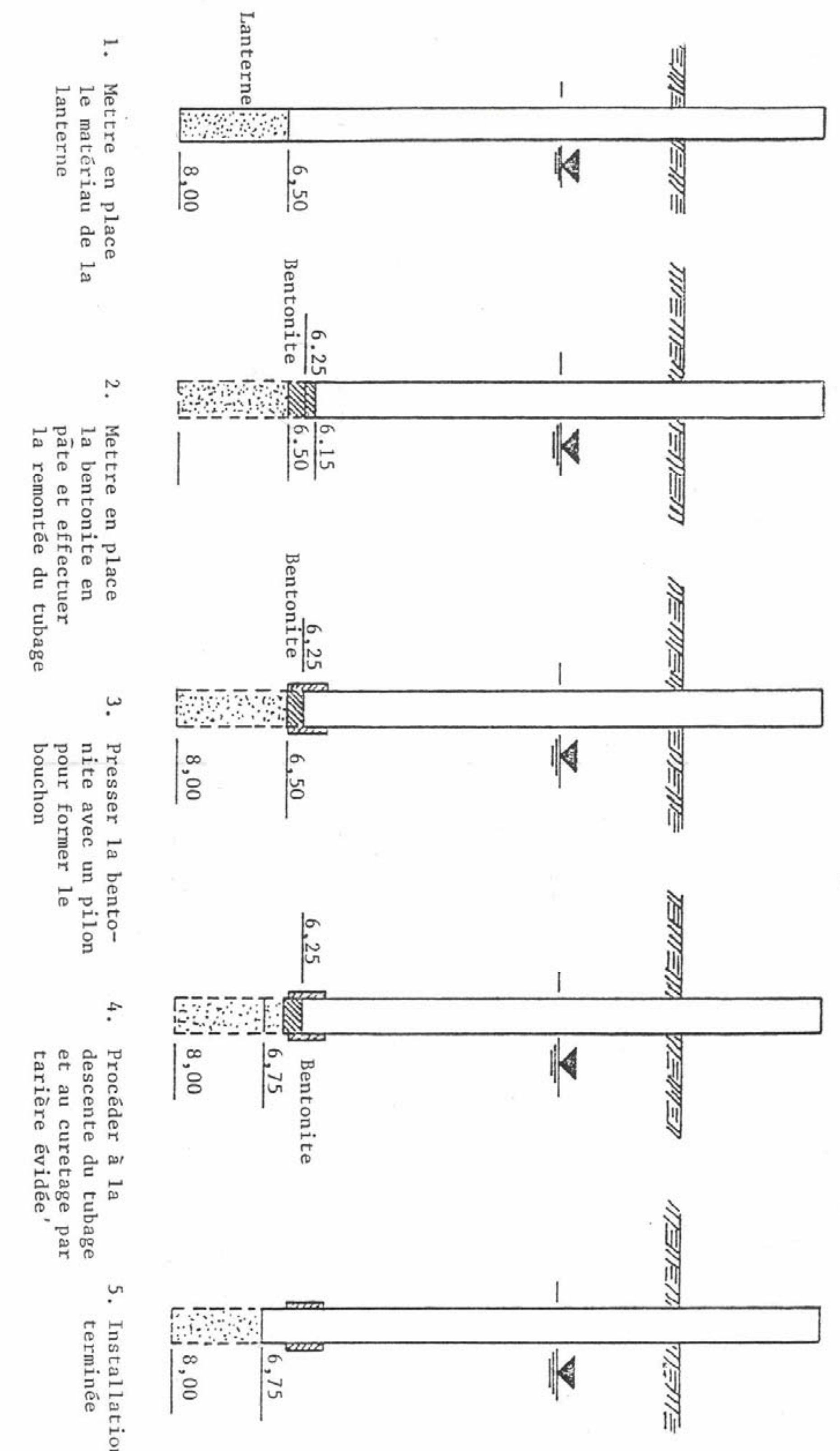
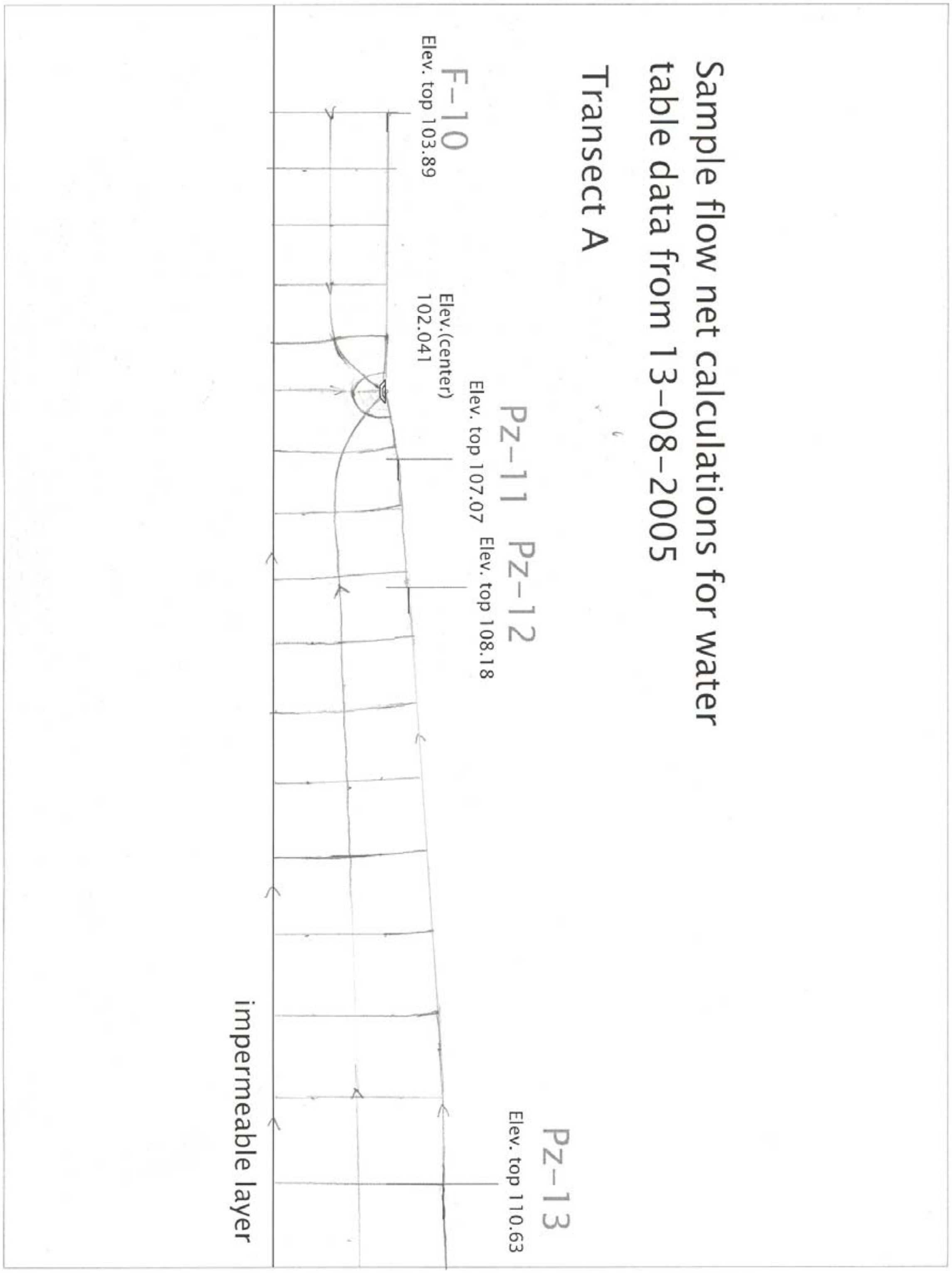
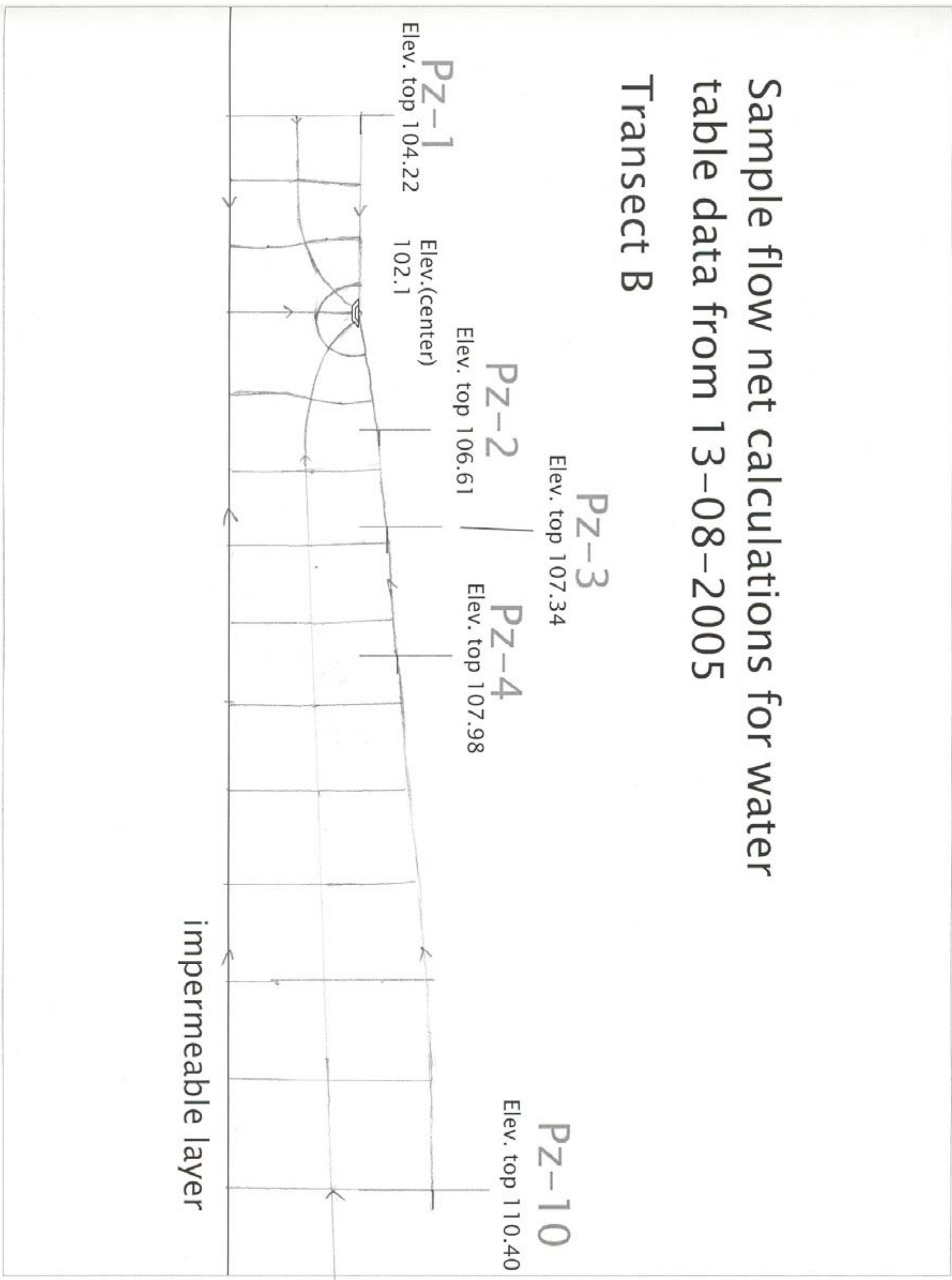


FIGURE 1 – PRÉPARATION DE LA LANTERNE ET MISE EN PLACE DU BOUCHON ÉTANCHE DE BENTONITE

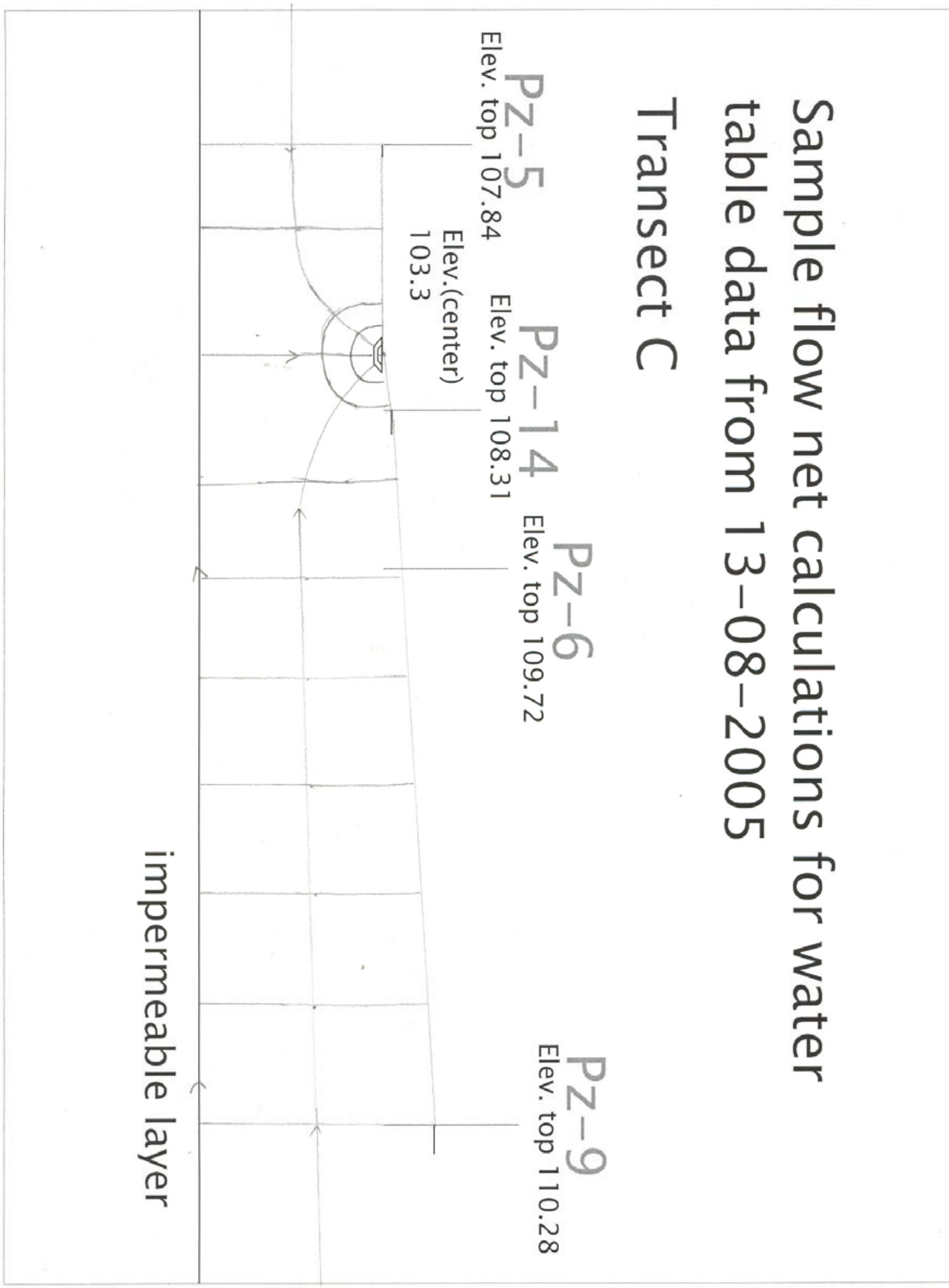
APPENDIX F: Example of flow net construction from St. Clet



APPENDIX F: Example of flow net construction from St. Clet continued



APPENDIX F: Example of flow net construction from St. Clet continued



APPENDIX G: Sample spreadsheet for flow net calculations

Sample spreadsheet calculations of flow for four days of sampled water table height at the St. Clet interceptor well.
Measured flows at the St. Clet pumphouse are shown at the end of the spreadsheet.

		Transect A								Transect B						
Date	side	k [m/s]	h_1 [m]	h_0 [m]	n_f	n_d	q [m^2/s]	L [m]	Q [m^3/s]	k [m/s]	h_1 [m]	h_0 [m]	n_f	n_d	q [m^2/s]	L [m]
13/08/2005	north	5.00E-05	106.42	101.941	2	11	4.07182E-05	153.4	0.00625	5.00E-05	106.8	102	2	10	0.0000483	149.8
	south	5.00E-05	102.09	101.941	2	6	2.48333E-06	153.4	0.00038	5.00E-05	102.1	102	2	3	3.6667E-06	149.8
21/08/2005	north	5.00E-05	106.4	101.941	2	11	4.05364E-05	153.4	0.00622	5.00E-05	106.8	102	2	10	0.0000483	149.8
	south	5.00E-05	102.13	101.941	2	6	3.15E-06	153.4	0.00048	5.00E-05	102.1	102	2	3	3.6667E-06	149.8
19/09/2005	north	5.00E-05	106.37	101.941	2	11	4.02636E-05	153.4	0.00618	5.00E-05	106.8	102	2	10	4.82E-05	149.8
	south	5.00E-05	102.25	101.941	2	6	5.15E-06	153.4	0.00079	5.00E-05	102.2	102	2	3	6E-06	149.8
04/10/2005	north	5.00E-05	106.34	101.941	2	11	3.99909E-05	153.4	0.00613	5.00E-05	106.8	102	2	10	0.0000478	149.8
	south	5.00E-05	102.18	101.941	2	6	3.98333E-06	153.4	0.00061	5.00E-05	102.2	102	2	3	5E-06	149.8

APPENDIX G: Sample spreadsheet for flow net calculations continued

	Transect C										
Q [m^3/s]	k [m/s]	h_1 [m]	h_0 [m]	n_f	n_d	q [m^2/s]	L [m]	Q [m^3/s]	Q_{total} [m^3/s]	Q_{total} [l/s]	$Q_{measured}$ [l/s]
0.007237272	5.00E-05	105.93	103.2	2	8	3.4125E-05	296.5	0.0101191	0.02360253		
0.000549413	5.00E-05	103.22	103.2	2	3	6.6667E-07	296.5	0.0001977	0.00112804		
									0.02473057	24.7	10.5
0.007237272	5.00E-05	105.92	103.2	2	8	0.000034	296.5	0.010082	0.02353757		
0.000549413	5.00E-05	103.22	103.2	2	3	6.6667E-07	296.5	0.0001977	0.00123031		
									0.02476788	24.8	10.5
0.007222288	5.00E-05	105.9	103.2	2	8	0.00003375	296.5	0.0100079	0.02340662		
0.00089904	5.00E-05	103.23	103.2	2	3	1E-06	296.5	0.0002965	0.00198558		
									0.0253922	25.4	10.7
0.007162352	5.00E-05	105.88	103.2	2	8	3.35E-05	296.5	0.0099338	0.02323071		
0.0007492	5.00E-05	103.23	103.2	2	3	1E-06	296.5	0.0002965	0.00165677		
									0.02488749	24.9	10.6