RAW WATER FOR AGRICULTURAL IRRIGATION STUDY – PHASE 2

TASK 5 TECHNICAL MEMORANDUM 1: CHANNEL CONVEYANCE EFFICIENCY

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1.0 Introduction

The Regional Municipality of Niagara (Region) retained Stantec Consulting Ltd. to complete a study identifying options for the provision of raw irrigation water to fruit, grape, and greenhouse growers in five municipalities, including Niagara on the Lake, St. Catharines, Lincoln, Grimsby, and Pelham. The objective of the overall study is to define a recommended irrigation strategy that is best able to meet the needs of the agricultural community in this area, while being financially feasible and environmentally sound.

This Technical Memorandum represents Task 5a of the overall Study and summarizes the work completed to define the general *conveyance efficiency* of an existing open channel irrigation system, with the ultimate goal of defining an economic and environmental valuation of the losses associated with such a system, as compared to other servicing approaches. Conveyance efficiency is discussed in more detail in Section 1.2.

1.1 BACKGROUND

Phase 1 of the irrigation study was completed in September of 2005, and contained identified solutions in terms of sources and distribution of irrigation water for the 5 municipalities. The Region then proceeded on to Phase 2: a more detailed approach to quantifying the various provisional estimates and assumptions made in the evaluation of the supply and distribution options laid out in the Phase 1 Final Report. There were two main distribution alternatives identified in the Phase 1 Final Report: pipeline distribution, and open channel distribution.

A pipeline distribution system is mainly composed of buried pipelines from the source to the consumers. An open channel distribution system, for the purpose of this study, is an irrigation distribution network using portions of natural watercourses and man-made open drainage systems to convey irrigation water to the farm's location. This type of distribution system is currently being used in Niagara on the Lake. The designation of "open channel distribution" does not preclude the use of some pipeline in the system. The irrigation water from some sources may have to be transmitted to the heads of the irrigation channels using pipelines. An open channel distribution system requires a fairly flat irrigation area preferably with a uniform gentle slope. The lands below the Escarpment have these characteristics. This distribution alternative was considered for the East District (Niagara on the Lake) and West District Zone A (St. Catharines and Lincoln below the escarpment).

The conveyance efficiency of an open channel distribution system is, in general, substantially lower than a pipeline system due to evaporation and seepage losses, operational wastes, and return flows. The conveyance efficiency is highly dependent on the management of the irrigation system. Environmental factors such as temperatures, humidity, and groundwater levels also have a major impact on the efficiency of the system (losses in drier years are generally higher than losses during a humid year). For the Phase 1 Final Report, a preliminary efficiency of 70% was used in all calculations. A more accurate estimate was deemed obtainable by a study of the conveyance efficiency of an existing open channel distribution system.

The Niagara on the Lake (NOTL) Municipal Irrigation System operates from mid-May until mid-September, providing irrigation water through municipal drains to some 4,000 acres of irrigated land. In addition to irrigation for plant water demand, the system provides water for frost protection during May for a number of berry growers. The current maximum system capacity is 15,000 USGPM (82,000 m^3/day or 800 acre-inches/day), using the Welland Canal, Niagara River and OPG facilities as sources. The supply system from the Niagara River was completed in 2005, including a pumped intake near the town of Queenston.

The distribution system is composed of a number of drains or irrigation channels conveying the irrigation water generally from south to north. These irrigation channels were considered for the conveyance efficiency study.

1.2 CONVEYANCE EFFICIENCY

For the purposes of this study, the conveyance efficiency of an irrigation distribution system is defined as the water conveyed to the end user as the percentage of the water removed from the supply source. In order to discover this amount of conveyance, a measurement of all losses in an irrigation distribution system between the source and the farm field needed to be made. Nevertheless, it should be noted that not all of the water that does not make it to the farmer is “wasted”, since part of it reaches the groundwater aquifers and may be used again. Furthermore, losses via return flow may also represent a benefit to downstream systems. Nevertheless, the water supplied to the system that is not utilized for the primary purpose of the system (irrigation) is considered to represent an inefficiency of the system.

As introduced within the Feasibility Study (August 2005), the relative conveyance efficiency of a given distribution system, be it open-channel or pipeline, represents an important parameter in the comparison of costs and efficiency of the utilization of water resources between systems.

Conveyance losses in an open-channel irrigation system are primarily comprised of seepage through the channel invert and banks, evapotranspiration, and leakage through structures such as gates and valves, with seepage typically representing the largest component of the total loss.

Though not typically considered to be a conveyance system inefficiency, the existence of flow at the downstream end of an open-channel distribution system (return flow) is also considered to be an important “loss” that does not occur within piped systems. While obviously undesirable from an operating efficiency perspective, this condition is essentially unavoidable within open-channel distribution systems since most downstream users have an expectation of service that leads to wastage when all of the water provided is not used.

2.0 Methodology

The objective of this study was to determine an accurate measure of losses that an open irrigation channel would produce during regular operation, as a parameter of comparison with closed systems. Since the concern was not to differentiate between types of losses (i.e. evapotranspiration vs. seepage), a flow measurement system was chosen to facilitate in quantifying losses. This would also facilitate in measuring return flow.

In consultation with staff from Agriculture and Agri-Food Canada/ Prairie Farm Rehabilitation Administration (AAFC/PFRA), the Town of NOTL's Irrigation Department, and Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA), two separate reaches of the NOTL system were selected for flow measurement. The two reaches chosen for the study were the Lavigne Drain and the Harrison 6 Drain. They were selected because of their relatively long reaches without flow splits or additions, and because they traveled through two relatively different soil types. The Lavigne is located in the western portion of the Town, where soils are typically finer than on the southeastern portion of the town. The top half of the Harrison 6 Drain flows through these more coarse soils. Figure 1 shows the location of the measurement structures with respect to established rain gauges on each system. Detailed maps of each system are located in Appendix A with symbols indicating approximate locations of the measurement structures. As discussed previously, flow traveling through the irrigation channels is generally from south to north. The distance between measuring stations was approximately 5.7 km for the Lavigne Drain and 7.5 km for the Harrison 6 Drain.

Measurement structures were set up at both ends of the systems, in order to capture as many of the system users as possible. By capturing nearly all users on the system, and using accurate measurement equipment, total losses could be determined. In simplest terms, the difference between the inlet flow (top of system) and the sum of the outlet flow (bottom of system) and known irrigation usage across the reach, represent the total losses for the system. In equation form:

$$\textit{Losses} = \textit{Supply} - (\textit{Return Flow} + \textit{Usage})$$

Figure 1: Locations of Weirs and Nearest Weather Stations

2.1 MEASUREMENT STRUCTURES AND EQUIPMENT

Following the recommendations of AAFC/PFRA, v-notch weirs were selected as the preferred flow measurement structures. The v-notch weirs offered the following advantages:

- most accurate of typical weir shapes through the widest range of heads / flows, particularly in the flow regime in the systems under study, and
- well established head-discharge relationships

The weirs were designed so that they would be able to easily capture all of the flow through the system without overflowing or structurally failing. Furthermore, they were to be constructed inexpensively. The weirs were constructed using two layers of pressure-treated 3/4" plywood fastened to t-bars and set into the channel, with cable anchors fastened to the t-bars as lateral support. The notch was cut at a 90-degree angle, and 1/8" metal strapping was fastened to the upstream side of the notch to provide a sharp edge for the water to fall over, improving the accuracy of measurements. Figure 2 through Figure 8 show photographs of the weir structures and data logging equipment (Figure 5 is a photograph of the bottom of Harrison 6 prior to the installation of the v-notch weir).

Figure 2: Top of the Lavigne Drain Looking Upstream

Figure 3: Top of the Lavigne Drain Looking Downstream

Figure 4: Bottom of the Lavigne Drain Looking Upstream

Figure 5: Bottom of Harrison 6 Drain Looking Downstream - No V-notch Installed

Figure 6: Top of Harrison 6 Drain Looking Downstream

Figure 7: Detail of V-notch Facing Upstream

Figure 8: Detail of Monitoring Station

Data logging equipment was installed at each site for the purposes of recording continuous depth of flow data[1]. Campbell Scientific data loggers and pressure transducers were supplied by AAFC/PFRA. Figure 8 shows the data-logging casing with battery. A 12-volt lead-acid battery attached to a 5-watt solar panel supplied power to the data logger.

The data logger was programmed to take a reading from the pressure transducer every 15 seconds, and then average these readings over hourly intervals, with only the hourly readings maintained. The program then converted the pressure reading into a height of water in meters; to which a corresponding flow (in m^3/s) was determined using the standard 90-degree v-notch formula:

$$Q_{v\text{-notch}} = C_d * 8/15 * (2g)^{1/2} * \tan(\theta/2) * H^{5/2}$$

where

C_d = 0.585
θ = 90˚
g = 9.81
H = Height (in meters)

[1] Pressure transducers and data loggers, as well as installation advice and assistance, were provided by Agriculture and Agri-food Canada.

2.2 DATA COLLECTION PERIOD

After several administrative delays, the weirs were installed at the end of July 2006 and remained in place for the duration of the irrigation season, which officially ended on September 15, 2006. At this point it was decided to run the system for a few days (September 15-19) with no users drawing and no foreseeable rainfall.

3.0 Results and Analysis

3.1 RESULTS

During the two months that the data loggers were operational, a variety of flow conditions occurred. The requirements for a meaningful mass balance analyses were met during a portion of this period. Interferences made a large portion of the data unusable for the purpose of mass balance analysis; including intermittent rainfall events, which would send runoff into the irrigation channels, and create peaks in the downstream data. Any rainfall meant that the system's sources (pumps, siphons) were shut off, cutting supply to the irrigation channels. Moreover, it was necessary to have constant flow supplied into the system for at least 24 hours to get an accurate measurement of conveyance, and on the Harrison 6 Drain, the pump that supplied water to the system was occasionally erratic. This made it impossible to come to a reliable estimate of seepage and evapotranspirative losses during these times of inconsistent supply.

Figure 9, Figure 10 and Figure 11 are charts of sections of data that were beneficial for efficiency calculations. Note that the downstream station data roughly follows the same pattern as the upstream data, but is delayed by a certain time period. With the NOTL open channel system, irrigation water is not constantly supplied. During wetter times, the system's pumps and siphons are shut off to conserve water and energy, and the channels mostly dry up. During dry periods, the users of the system begin using supplied raw water for irrigation. However, there is a delay from the initial supply of water at the supply point to the time when sufficient water reaches different points along the irrigation channel. This is attributable to the passive volume in the channel that must be filled. Figure 9 and Figure 10 illustrate the flow rates for both monitoring stations on the Lavigne and Harrison 6 Drains, respectively.

For the Harrison 6 system, this delay was about 24 hours to completely supply the 7.5 km length of the irrigation channel. The Lavigne system delay was about 18 hours. We expect these delay times to vary with initial moisture content of the channel, flow rate, and amount of usage upstream. However, both systems averaged approximately 3.2 hours of delay per km. Based on approximate flow rates of 1,100 USGPM (250 m^3/hr) and 1,050 USGPM (240 m^3/hr) for the Lavigne and Harrison 6 drains, respectively, the filling volumes for these systems are approximately 0.8 m^3 per meter length of the channel.

Sections of the downstream graphs will show a diurnal pattern. This is attributable to the fact that evapotranspiration decreases at night. When irrigation is occurring, then the downstream graph will show lower flow during the day, with flows increasing overnight as users shut off their individual irrigation systems.

Figure 9 shows both measured flows rise rapidly at the end of the period. This corresponds to a rainfall event on September 19. All rainfall was confirmed by data received from Weather Innovations (WIN), who operates rain gauges in the area. Figure 1 shows the rain gauges that were located in the vicinity of the monitoring stations. Confirmation of occurrence and timing of rainfall events was made using the data provided by WIN.

Figure 9 - Flow Through Lavigne Drain

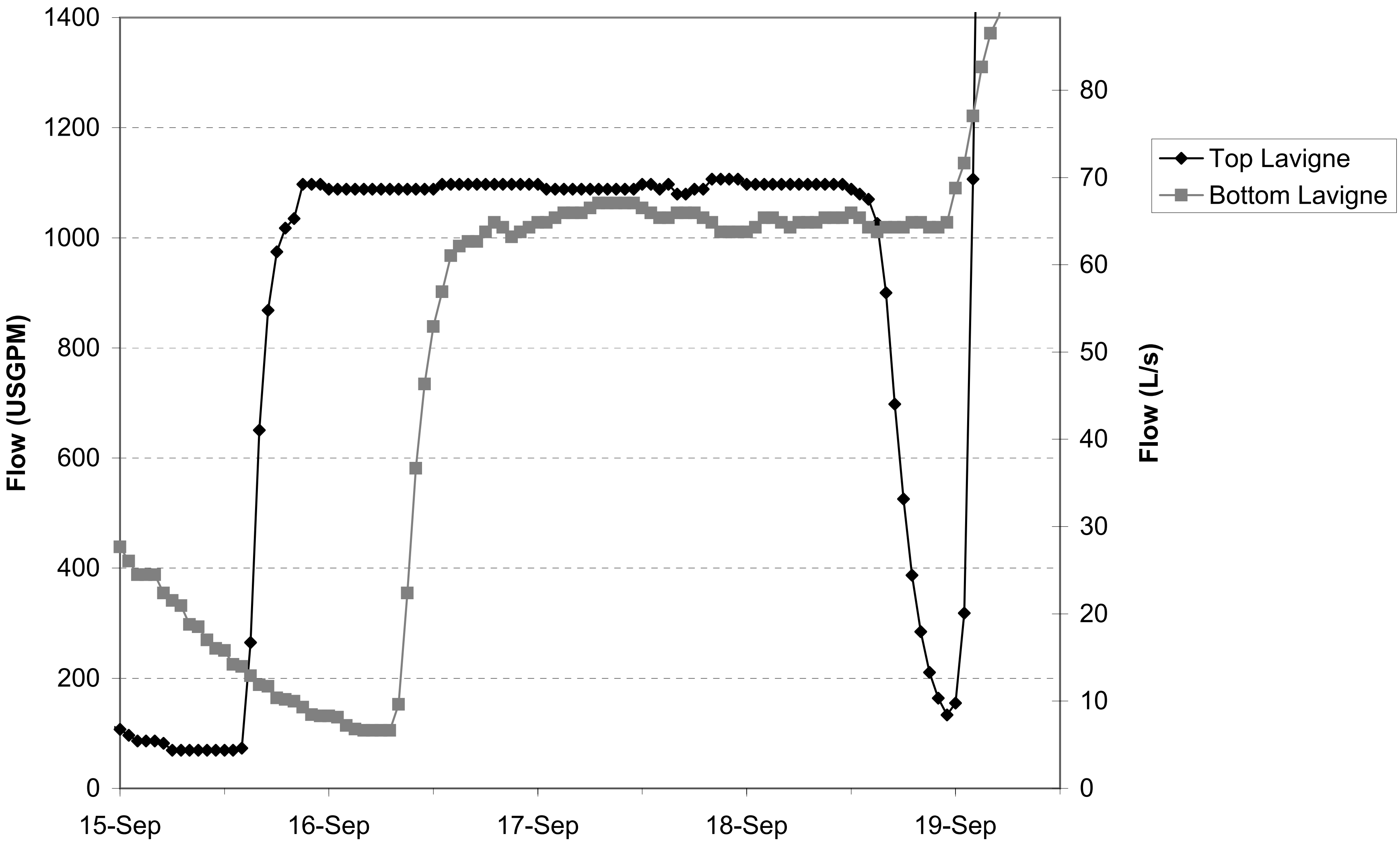


Figure 10 - Flow Through Harrison 6 Drain

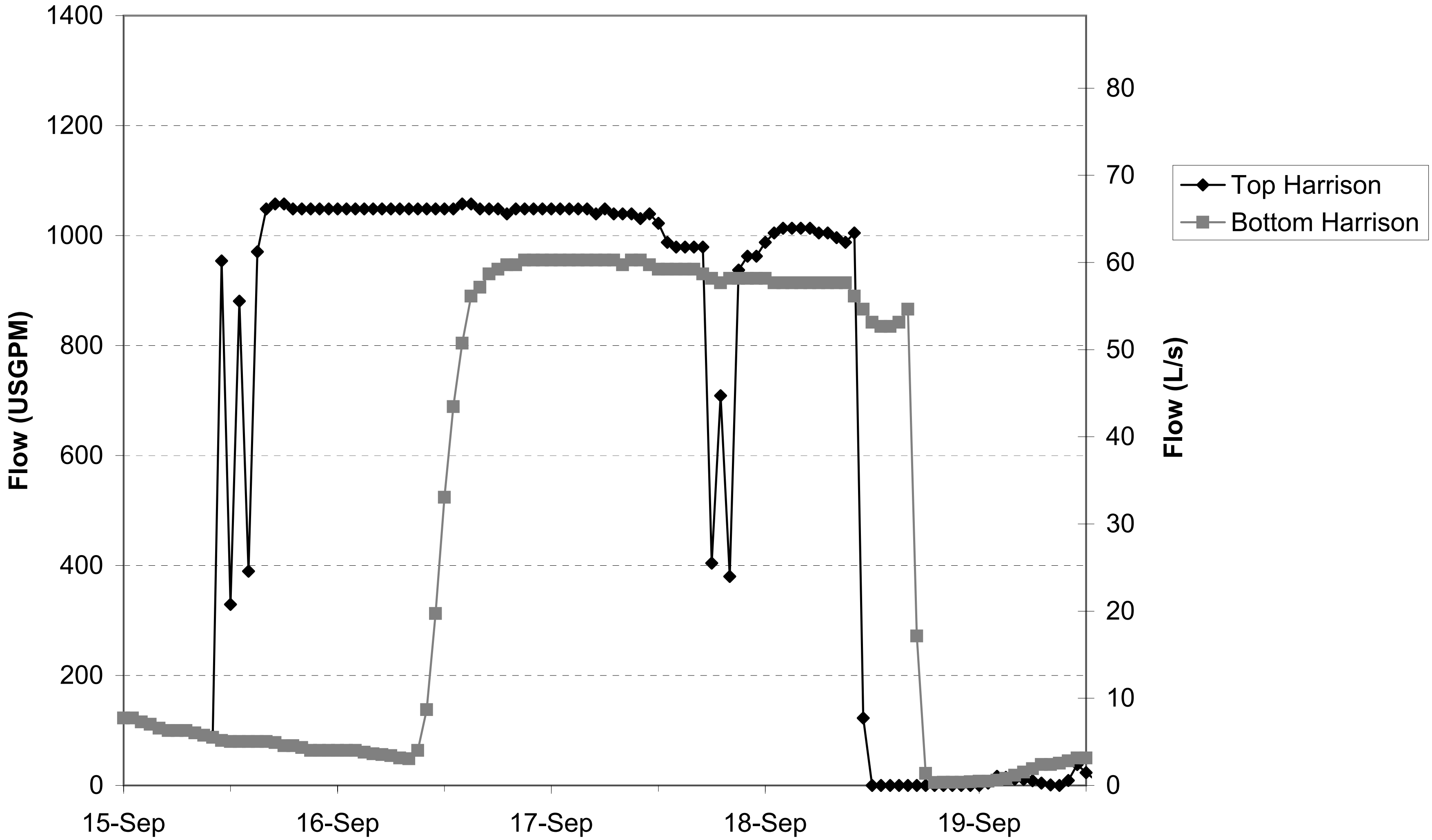
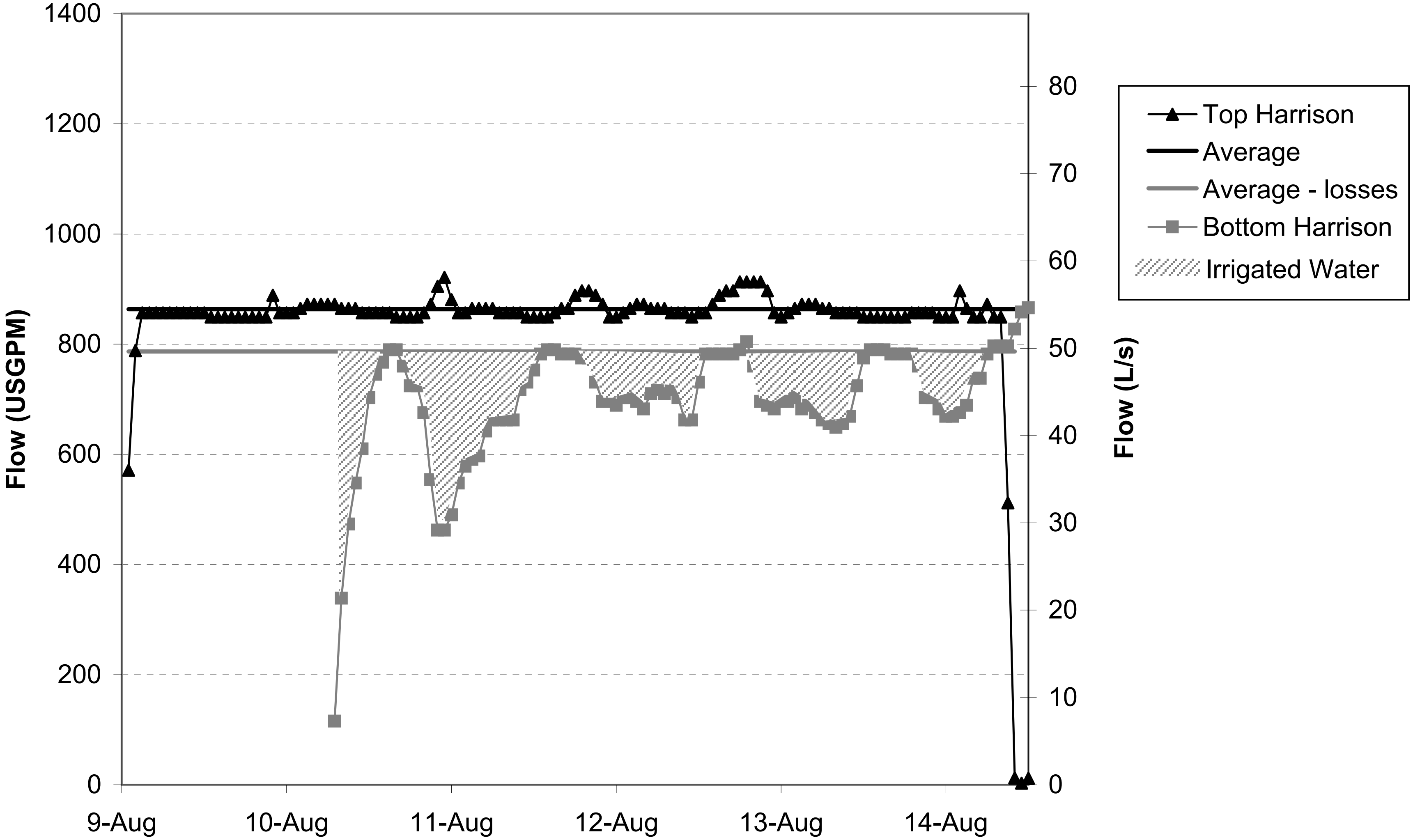


Figure 11 - Flow Through Harrison 6 Drain



3.2 ANALYSIS

3.2.1 Seepage and Evapotranspiration Losses

The most accurate measurement of losses was for the duration that each system was running in September with no users drawing water. Figure 9 illustrates the flow rates for both monitoring stations on the Lavigne Drain. The average flow supplied to the upstream end of the system was 1093 USGPM (68.96 L/s) whereas the average flow out of the downstream end of the system was 1031 USGPM (65.05 L/s). This amounts to a total loss of 1% per km due to seepage and evapotranspiration. For this system (with a 5.7 km reach) this represents a seepage and evapotranspirative loss of 89,250 US gal (338,000 L) per day.

The data from the two flow monitors for the Harrison 6 Drain are shown in Figure 10. The average flow supplied to the upstream end of the system was 1048 USGPM (66.12 L/s), while the average flow out of the downstream end of the system was 955 USGPM (60.25 L/s). This amounts to a total seepage and evapotranspirative loss of 1.2% per km or 134,000 US gal (507,000 L) per day for the 7.5 km reach. The supply pump was stable enough to arrive at these figures; however, some irregularities in the supply curve are demonstrated in Figure 10.

The difference in seepage between the two systems may be explained by the more clayey soil located on a major portion of the Lavigne system, whereas the Harrison 6 system flows through more sandy soils. However, the difference found is small, and may not be significant considering the measurement precisions.

These measurements were made during September when the soil moistures were relatively high and evaporation was relatively low compared to the rest of the season. We should, therefore, expect that the observed losses are at the lower limit of the range of losses occurring during the irrigation season.

3.2.2 Estimated Usage

On the Harrison 6 system, four days of data were collected in August where there was continuous artificial flow into the system, and no rainfall. Given the controlled nature of the inputs to the system during this period, analysis of the return flow out of the system could be used to estimate the seepage and evapotranspirative losses, as well as usage of water by the farms on the system. Figure 11 displays these four days of data and the calculated usage for the system.

The usage volumes were calculated by first averaging the flows supplied to the top of the system for the duration of these four days. The average is 863 USGPM and is shown as a solid line in the above figure. The losses due to seepage and evapotranspiration measured for this system (from Figure 9) were subtracted from the average flow at the top end. This would give a basis (maximum) flow for the bottom of the system, represented by the solid grey line (average flow in minus losses). In other words, this line shows how much return flow would be expected out of the system if no users were taking water (787 USGPM). The periodic fluctuating grey line shows the actual measured flow at the bottom of the Harrison 6. The diurnal pattern observed is as expected with the peaks occurring overnight when irrigation is not occurring and all accounted losses are “natural”. These peaks correspond fairly accurately with the calculated average maximum using the data obtained in September – displayed in solid grey.

The area of the curves between the average losses and the observed return flow (indicated by hatched area) represents the total irrigated water in gallons. For this period, the total irrigated water was 419,000 US gallons. Since the system ran for four days, this amounts to 104,775 gal/day (1,586,000 L/day), or 3.86 acre-inches/day.

These data do not potentially reflect the usage throughout the rest of the irrigation season, nor throughout other systems within the overall NOTL system. However, they provide a picture of the relatively small amount of irrigation water that is used when compared to the amount of supplied water, which may often occur during the irrigation season. The low usage, hence the low apparent system efficiency, may be attributed to the relatively cool and wet periods prior to and during the overall data collection.

Similar data analysis was performed on the Lavigne system, with the summarized results shown in section 3.2.4 Summary.

3.2.3 Return Flow

From Figure 11 we can also calculate actual return flow for the system during the four-day period. For the 7.5 km long Harrison 6 system this amounts to 4,110,000 gallons over the four days of operation at an average of 714 USGPM. Although this data set is diminutive, it is implicit in the information gathered that return flow accounts for the majority of flow supplied to the system during this low irrigation demand period.

3.2.4 Summary

The Harrison 6 system exhibited the following statistics for that four-day period:

Seepage and Evapotranspiration Losses:	8.9 %
Irrigation Usage:	8.4 %
Return flow:	82.7 %

Using a similar method for two separate 3-day periods on the 5.7 km long Lavigne system produced the following results:

Seepage and Evapotranspiration Losses:	5.7 %
Irrigation Usage:	8.3 %
Return flow:	86.0 %

3.3 BASEFLOW ESTIMATE

When each system's supply was turned off for any extended duration, the downstream monitoring station still collected data. This allowed for an assessment of baseflow for each irrigation channel. The Harrison 6 Drain is relatively flat, and when the supply was shut off, it took approximately 24 hours for the flow at the downstream end to cease. Without the numerous dams set up by users on the channel, it is expected that the entire length of the system would dry up in a matter of days. With this limited amount of data over one season, the conclusion is that there is no baseflow into this system. This could potentially change with seasonal or annual fluctuating groundwater elevations.

The Lavigne system never dried up entirely during the monitoring. Due to the expansive header that supplies the system, there was always flow going into the upstream station, and flow continued through the downstream end. Since the flow coming out the bottom end of the system was always substantially less than what was being fed in (except in the case of rainfall events), it can be assumed that there was no groundwater feeding into this system and baseflow equals zero. However, this is again based on a small amount of data collected over one season, and the baseflow could fluctuate year-to-year or season-to-season.

4.0 Discussion

This report set out to quantify the conveyance efficiency of an open channel distribution system for irrigation with raw water, in terms of seepage, evapotranspiration and return flow. We were surprised at the size of the return flow compared to the seepage and evapotranspiration losses.

A major component of the loss to return flow is what we have called the delay loss. The delay loss – the amount of water that is needed to fill the irrigation channels in order to allow the system to operation at full flow – becomes return flow when the system is shut down. Delays were measured and deemed sufficiently accurate. It was concluded that the water required to fill the irrigation channels – the delay loss – was approximately 0.8 m^3 per meter length of the irrigation channels for the typical irrigation channels used in Niagara-on-the-Lake. For a 5 km long channel, the delay loss is in estimated at 4,000 m^3 (1 million US gallons or 3.2 acre-ft). This has an important implication for the operation of the system. It is not feasible to react to day-to-day variation in demand, due to the fact that users need to draw water from any location along the entire reach of the system. The system can only shut down during the season if we know that there would not be demand for a few days. This conclusion is supported by the observed operation of the system.

The return flow was high during the study period, due to this period's low irrigation water consumption. Return flow was directly affected by irrigation usage. Return flows of 80 to 90% were estimated. The operator has little control in terms of adjusting the supply to the day-to-day demand variations. Therefore, the return flow is inversely proportional to the demands, except for the periods when there is obviously no demand for a few days – such as after a significant rainfall, when the system can be turned off for a few days.

The findings on the return flow will not significantly affect the system capacity requirements, because the flow capacity of the system will be based on the high demand periods, during which return flows are low. However, the high return flows during low demand periods will substantially increase seasonal water takings. Furthermore, pumping costs are expected to be substantially higher for the open channel distribution system due to pumping large quantities return flow throughout the irrigation seasons.

By measuring the total flow into and out of the system during non-irrigation periods, total seepage and evapotranspiration losses were determined to be approximately 1% per km for the Lavigne system, and 1.2% per km for the Harrison 6 system, giving an average of 1.1% per km. The difference between the two systems can be explained by the relatively more clayey soil located on a major portion of the Lavigne system (however, the difference may not be significant within the measurements precision range). For a 5 km long irrigation channel, a loss of 5 to 6% is estimated during relatively wet and cool periods. The losses are likely to be somewhat higher during dry and hot periods.

The "FEASIBILITY STUDY – RAW WATER FOR AGRICULTURAL IRRIGATION PURPOSES PROJECT REPORT" assumed a conveyance efficiency of 70% for open channel distribution systems. Given some 10% loss to evaporation and seepage, this would assume a 20% return flow. An average 20% return flow during peak irrigation periods is reasonable if we were to ensure that the users close to the downstream end of the system were fully serviced. However, this may be overly optimistic as an estimation of the seasonal conveyance efficiencies. The conveyance efficiencies during our observation period were 5 to 10%. We suggest that the efficiencies of an open channel system in the Niagara region will likely range between 10% and 70% during the season.

Due to the fact that the irrigation season in 2006 was a relatively wet season, and as stated above, demand was low, it can be surmised that for ultimate demand, efficiency will increase. However, what cannot be ignored is that during wet seasons, the water takings for irrigation will have a relatively low efficiency, and therefore will be much higher than a piped system would be for the same year.

5.0 Conclusions

Based on the data collected during this study, we have concluded that the major component of conveyance efficiency of open channel systems in Niagara is return flow. Return flow is more pronounced during low demand periods than high demand periods. Also, every system shut-down during the season will entail a significant loss of water for re-filling the channels.

We have estimated the following efficiency for the open channel distribution systems:

A conveyance efficiency of 70%, as recommended by the "FEASIBILITY STUDY – RAW WATER FOR AGRICULTURAL IRRIGATION PURPOSES PROJECT REPORT" is supported for peak demand periods. This efficiency will be used to size the infrastructure, such as intakes, pumps, transmission components and distribution channels.

It should be noted that for average seasonal water takings, the efficiency will decrease, and therefore pumping requirements will not be directly proportional to demand. An average conveyance efficiency could not be drawn from the limited findings in this report, however, it is expected to be near to 40%, and is dependant on the length of the system, as well as level of automation and management practices.

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APPENDIX A

Map of Irrigation Systems

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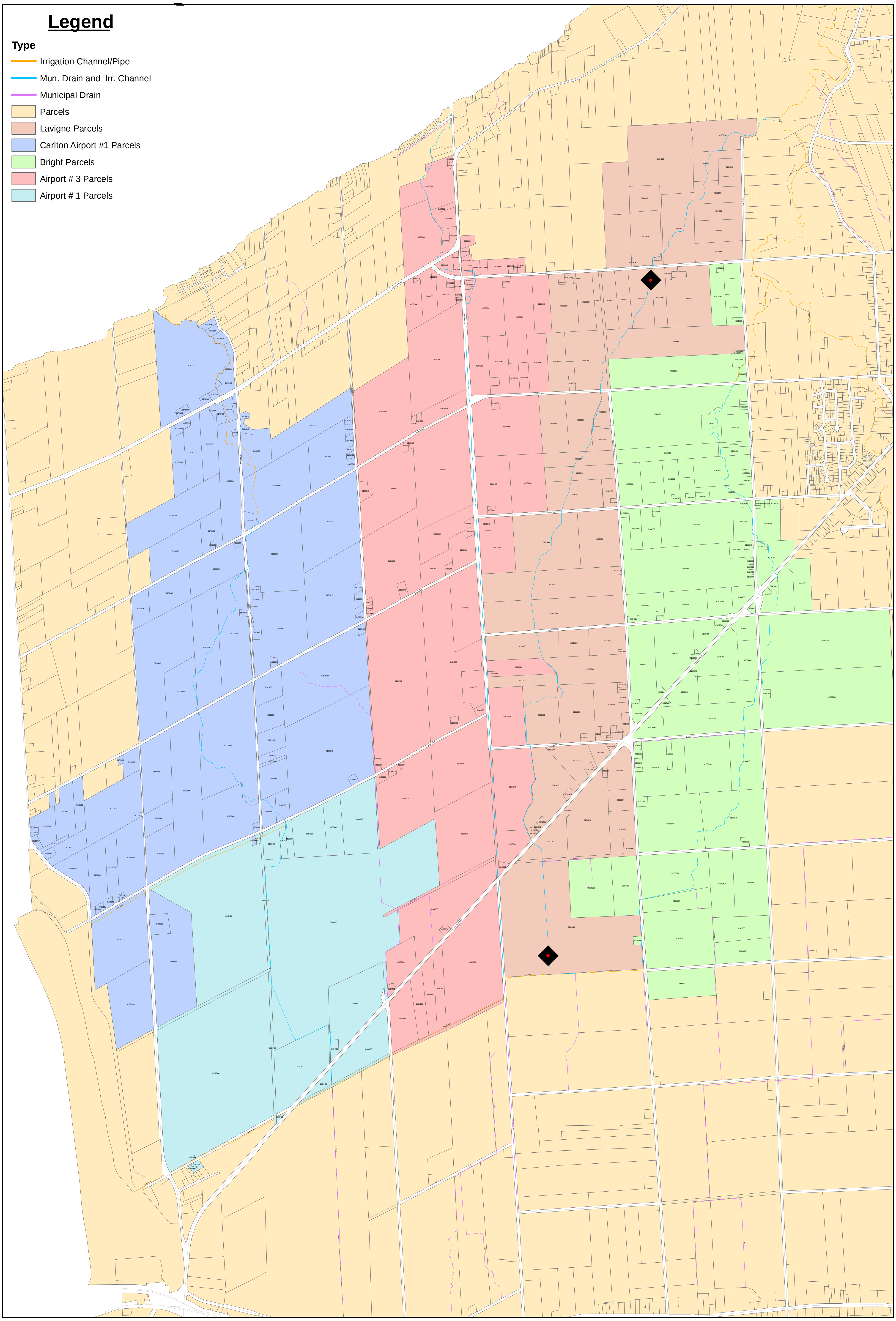
Date : March 23, 2005
h:\GIS\Drawings\ArcView\Municipal Drains\ABLJan2005.mxd

Town of Niagara-on-the-Lake

Airport Bright Lavigne Irrigation System



By : Mike Komljenovic
Dept : Engineering Department
Date : March 23, 2005
h:\GIS\Drawings\ArcView\Municipal Drains\Harrison Jan2005.mxd

Town of Niagara-on-the-Lake

Harrison Routh Irrigation System