PUMP SCHEDULING AND RESERVOIR RELEASES FOR THE OPTIMIZATION OF WATER SUPPLY SYSTEM OPERATING COSTS

by

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ABSTRACT

The main goal of this project was to optimize pump scheduling and reservoir releases for the Regional Municipality of Ottawa-Carleton's (RMOC) water supply system. The first objective was to identify, through application of an *optimization model* (OM), the potential savings from improved pump scheduling for RMOC's water supply system. A computer model was designed to optimize electricity costs at RMOC's water purification plants (WPPs) using linear programming (LP) with a *Borland's* Quattro Pro spreadsheet and its built-in LP solver called ***Optimizer***. The model has two levels of optimization: Level I, solving for pumping times and Level II, creating pump schedules. Model results were compiled for typical summer and winter days and monthly estimates were compared to the WPPs electricity bills. Although the model was not calibrated, energy costs were within 5% of the electricity bills.

The second objective was to study the impact of different water management alternatives on energy costs. The alternatives considered were: (i) increasing operating volumes in the Billings Bridge and the Glen Cairn/Stittsville branches; (ii) increasing the treatment capacity at the Lemieux Island WPP; and (iii) considering a larger pipe size and additional smaller pumps in the Hurdman Bridge branch. Except for slight increases in operating volume that can be achieved by reevaluating safety coefficients on the minimum allowable reservoir storage volume, all these alternatives involve new construction. Significant energy savings can be achieved by implementing these alternatives but construction costs are very large. Factors other than economical are needed to justify implementing these water management alternatives but the energy savings are certainly an incentive in terms of dampening high construction costs. The major benefits reside in the simpler and more economical day-to-day operations.

Although it is based on historical data instead of demand forecasting modules and hydraulic simulators, and although it is not designed for real-time, our model is designed as a first attempt to quantify potential energy savings and as a decision making tool for RMOC's water supply efficiency concerns.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS i
ABSTRACT ii
TABLE OF CONTENTS iv
LIST OF TABLES vii
LIST OF FIGURES xiii
GLOSSARY xvii

CHAPTER 1 - INTRODUCTION 1
1.1 CHARACTERISTICS OF OPERATIONS OPTIMIZATION MODELS 1
1.2 THE REGIONAL MUNICIPALITY OF OTTAWA-CARLETON (RMOC) ... 3
1.2.1 RMOC's Water Supply System 4
1.2.2 Ottawa Hydro's Rate Structure 6
1.2.3 Water And Electricity Management 8

CHAPTER 2 - LITERATURE REVIEW 9
2.1 OPERATIONS OPTIMIZATION IN WATER SUPPLY DISTRIBUTION SYSTEMS 9
2.1.1 General Problem 9
2.1.2 Examples 12
2.1.3 Mathematical Considerations 13
2.1.4 Other Aspects Of Water Supply Operations Optimization 14
2.1.5 Other Types Of Optimization In Water Supply Distribution Networks 14
2.2 OPTIMIZATION IN WATER RESOURCES 16
2.2.1 Water Reservoirs 16

2.2.2 Water And Waste Treatment 17

2.2.3 Hydroelectric Systems 18

CHAPTER 3 - THEORY 21

3.1 THE LINEAR PROGRAMMING PROBLEM 22

3.1.1 Level I Optimization - Solving For Pumping Times 23

3.1.2 Level II Optimization - Creating A Pump Schedule 29

CHAPTER 4 - NOMENCLATURE AND METHODOLOGY 30

4.1 DATA USED 30

4.1.1 Hurdman Bridge Branch 31

4.1.2 Billings Bridge Branch 32

4.1.3 Carlington Heights Branch 32

4.1.4 Glen Cairn/Stittsville Branch (Including Barrhaven Sub-Branch) 33

4.2 ELECTRICITY RATES 34

4.3 *BORLAND'S* QUATTRO PRO SPREADSHEET AND THE *OPTIMIZER* TOOL 35

4.2.1 Level I - Optimization 36

4.2.2 Level II - Optimization 38

CHAPTER 5 - RESULTS 41

5.1 LEVELS I AND II OPTIMIZATIONS RESULTS 41

5.1.1 Hurdman Bridge Branch 42

5.1.2 Billings Bridge Branch 44

5.1.3 Carlington Heights Branch 46

5.1.4 Glen Cairn/Stittsville Branch 48

5.1.5 Barrhaven Sub-Branch 50

5.2 COMPILATION OF DAILY ENERGY COSTS 51

5.2.1 Typical Summer Day In July: Most Critical Period 52

5.2.2 Typical Winter Day In January 54
5.2.3 Analysis Of Total Energy Costs At The WPPs: Summer And Winter 55
5.3 ANALYSIS OF DIFFERENT WATER MANAGEMENT ALTERNATIVES 56
5.3.1 Analysis of Glen Cairn/Stittsville Branch 57
5.3.2 Analysis Of Carlington Heights Branch 62

CHAPTER 6 - DISCUSSION 67
6.1 COMMENTS ON THE DATA USED 67
6.2 MINOR BRANCHES AND SUB-BRANCH 70
6.2.1 Hurdman Bridge Branch 71
6.2.2 Billings Bridge Branch 72
6.2.3 Barrhaven Sub-Branch 73
6.3 MAJOR BRANCHES 74
6.3.1 Carlington Heights Branch 75
6.3.2 Glen Cairn/Stittsville Branch 76

CHAPTER 7 - CONCLUSIONS 79

CHAPTER 8 - RECOMMENDATIONS FOR FUTURE RESEARCH 82

CHAPTER 9 - APPENDICES 83
APPENDIX A : Tables 84
APPENDIX B: Figures 85
APPENDIX C: Models 86
APPENDIX D: Ottawa Hydro Rates and WPPs' Bills 87

CHAPTER 10 - REFERENCES 88

LIST OF TABLES

Table		Page
1.1	Population And Area Of RMOC'S Municipalities And Sub-Areas (1991)	A1
1.2	Ottawa Hydro 1993 Electricity Rates Used In The Model	A1
1.3	Restricted Hours Schedule Throughout The Year	A2
4.1	Hurdman Bridge Branch Electrical Pump Combinations (HB1E)	A3
4.2	Hurdman Bridge Branch Reservoir Operations Characteristics (R1E)	A3
4.3	Billings Bridge Branch Electrical Pump Combinations (BB2C)	A3
4.4	Billings Bridge Branch Reservoir Operations Characteristics (R2C)	A4
4.5a	Carlington Heights Branch Britannia 1W Pumps (BR1W)	A4
4.5b	Carlington Heights Branch Lemieux Island 1W Pumps (LI1W)	A4
4.5c	Carlington Heights Branch Fleet Street 1W Pumps (FS1W)	A4
4.6	Carlington Heights Branch Electrical Pump Combinations (BR1W, LI1W+FS1W, FS1W)	A5
4.7	Carlington Heights Branch Reservoir Operations Characteristics (R1W)	A5
4.8a	Glen Cairn/Stittsville Branch Britannia 2W Pumps (BR2W)	A6
4.8b	Glen Cairn/Stittsville Branch Carlington Heights 2W Pumps (CH2W)	A6
4.9	Glen Cairn/Stittsville Branch Electrical Pump Combinations (BR2W, CH2W)	A6
4.10	Barrhaven Sub-Branch Pumps (BHPS)	A7
4.11	Barrhaven Sub-Branch Electrical Pump Combinations (BHPS)	A7

Table		Page
4.12a	Glen Cairn/Stittsville Branch Reservoir Operations Characteristics (R2W)	A8
4.12b	Barrhaven Sub-Branch Reservoir Operations Characteristics (RBAR)	A8
4.13	Electricity Rates: Step Functions For Peak Usage	A8
4.14	Example Of Hourly Coefficients For Selected Pump Combinations (Glen Cairn/Stittsville Branch For A Typical Summer Night)	A9
4.15	Example Of Hourly Water Balance Or Pump Schedule (Glen Cairn/Stittsville Branch For A Typical Summer Night)	A9
5.1	Hurdman Bridge Pump Schedule For A Typical Summer Night	A10
5.2	Hurdman Bridge Pump Schedule For A Typical Summer Day	A10
5.3	Hurdman Bridge Pump Schedule For A Typical Winter Night	A11
5.4	Hurdman Bridge Pump Schedule For A Typical Winter Day	A11
5.5a	Billings Bridge Pump Schedule For A Typical Summer Night	A12
5.5b	Billings Bridge Hourly Coefficients For A Typical Summer Night	A12
5.6a	Billings Bridge Pump Schedule For A Typical Summer Day	A13
5.6b	Billings Bridge Hourly Coefficients For A Typical Summer Day	A14
5.7	Billings Bridge Pump Schedule For A Typical Winter Night	A14
5.8a	Billings Bridge Pump Schedule For A Typical Winter Day	A15
5.8b	Billings Bridge Hourly Coefficients For A Typical Winter Day	A16
5.9	Carlington Heights Pump Schedule For A Typical Summer Night	A17
5.10a	Carlington Heights Pump Schedule For A Typical Summer Day	A18
5.10b	Carlington Heights Hourly Coefficients For A Typical Summer Day	A18
5.11	Carlington Heights Pump Schedule For A Typical Winter Night	A19
5.12a	Carlington Heights Pump Schedule For A Typical Winter Day	A21

Table		Page
5.12b	Carlington Heights Hourly Coefficients For A Typical Winter Day	A22
5.13a	Glen Cairn/Stittsville Pump Schedule For A Typical Summer Night	A23
5.13b	Glen Cairn/Stittsville Hourly Coefficients For A Typical Summer Night	A24
5.14a	Glen Cairn/Stittsville Pump Schedule For A Typical Summer Day	A25
5.14b	Glen Cairn/Stittsville Hourly Coefficients For A Typical Summer Day	A26
5.15a	Glen Cairn/Stittsville Pump Schedule For A Typical Winter Night	A27
5.15b	Glen Cairn/Stittsville Hourly Coefficients For A Typical Winter Night	A28
5.16a	Glen Cairn/Stittsville Pump Schedule For A Typical Winter Day	A29
5.16b	Glen Cairn/Stittsville Hourly Coefficients For A Typical Winter Day	A30
5.17	Barrhaven Pump Schedule For A Typical Summer Night	A31
5.18a	Barrhaven Pump Schedule For A Typical Summer Day	A31
5.18b	Barrhaven Hourly Coefficients For A Typical Summer Day	A32
5.19	Barrhaven Pump Schedule For A Typical Winter Night	A32
5.20a	Barrhaven Pump Schedule For A Typical Winter Day	A33
5.20b	Barrhaven Hourly Coefficients For A Typical Winter Day	A34
5.21a	Britannia WPP Summer Energy Costs	A35
5.21b	Lemieux Island WPP Summer Energy Costs	A35
5.21c	Compilation Of WPPs' Summer Energy Costs	A36
5.22a	Hurdman Bridge Summer Energy Costs	A37
5.22b	Billings Bridge Summer Energy Costs	A37
5.22c	Carlington Heights 2W Summer Energy Costs	A38
5.22d	Barrhaven Summer Energy Costs	A38

Table		Page
5.23a	Britannia WPP Winter Energy Costs	A39
5.23b	Lemieux Island WPP Winter Energy Costs	A39
5.23c	Compilation Of WPPs' Winter Energy Costs	A40
5.24a	Hurdman Bridge Winter Energy Costs	A41
5.24b	Billings Bridge Winter Energy Costs	A41
5.24c	Carlington Heights 2W Winter Energy Costs	A42
5.24d	Barrhaven Winter Energy Costs	A42
5.25a	Britannia WPP Summer Energy Costs (Power Factor For Treatment At Lemieux Island WPP = 80 kW.h/ML)	A43
5.25b	Lemieux Island WPP Summer Energy Costs (Power Factor For Treatment At Lemieux Island WPP = 80 kW.h/ML)	A43
5.25c	Compilation Of WPPs' Summer Energy Costs (Power Factor For Treatment At Lemieux Island WPP = 80 kW.h/ML)	A44
5.26a	Britannia WPP Winter Energy Costs (Power Factor For Treatment At Lemieux Island WPP = 80 kW.h/ML)	A44
5.26b	Lemieux Island WPP Winter Energy Costs (Power Factor For Treatment At Lemieux Island WPP = 80 kW.h/ML)	A45
5.26c	Compilation Of WPPs' Winter Energy Costs (Power Factor For Treatment At Lemieux Island WPP = 80 kW.h/ML)	A46
5.27a	Britannia WPP Summer Energy Costs (Power Factor For Treatment At Lemieux Island WPP = 75 kW.h/ML)	A47
5.27b	Lemieux Island WPP Summer Energy Costs (Power Factor For Treatment At Lemieux Island WPP = 75 kW.h/ML)	A47
5.27c	Compilation Of WPPs' Summer Energy Costs (Power Factor For Treatment At Lemieux Island WPP = 75 kW.h/ML)	A48
5.28a	Britannia WPP Winter Energy Costs (Power Factor For Treatment At Lemieux Island WPP = 75 kW.h/ML)	A49

Table Page

5.28b Lemieux Island WPP Winter Energy Costs (Power Factor For Treatment At Lemieux Island WPP = 75 kW.h/ML) A49

5.28c Compilation Of WPPs' Winter Energy Costs (Power Factor For Treatment At Lemieux Island WPP = 75 kW.h/ML) A50

5.29a Britannia WPP Summer Energy Costs With CH2W Offline A51

5.29b Lemieux Island WPP Summer Energy Costs With CH2W Offline A51

5.29c Compilation Of WPPs' Summer Energy Costs With CH2W Offline A52

5.30a Britannia WPP Winter Energy Costs With CH2W Offline A53

5.30b Lemieux Island WPP Winter Energy Costs With CH2W Offline A53

5.30c Compilation Of WPPs' Winter Energy Costs With CH2W Offline A54

5.31 Maximum Operating Volume Of Reservoir R2W With Increasing Demand And CH2W Offline A55

5.32 Maximum Operating Volume Of Reservoir R2W With Increasing Demand And CH2W Online A56

5.33 Maximum Target Water Velocities With Increase In Pipe Constraint A57

5.34 Carlington Heights Branch LI1W+FS1W Electrical Pump Combinations A58

5.35 Carlington Heights Branch Electrical Pump Combinations (BR1W, LI1W+FS1W, FS1W) A59

5.36 Power Consumption Factors Of Carlington Heights Branch New Pump Combinations A60

5.37 Maximum Operating Volume Of R2C Reservoir In Billings Bridge Branch With Increase In Pipe Constraint A60

5.38a Maximum Operating Volume Of R1E Reservoir In Hurdman Bridge Branch With Increasing Water Demand A61

5.38b Maximum Operating Volume Of R2C Reservoir In Billings Bridge Branch With Increasing Water Demand A61

Table		Page
5.39	Maximum Operating Volume Of R1W Reservoir In Carlington Heights Branch With Increasing Water Demand And Increase In Pipe Constraint Of 25.0%	A62
6.1	Approximate Potential Savings at the WPPs for Different Water Management Alternatives	A63

LIST OF FIGURES

Figure		Page
1.1a	Map Of RMOC: Municipalities	B1
1.1b	Map Of RMOC: Regional Growth	B2
1.2	Urban Land Uses in RMOC (1991)	B3
1.3	RMOC's Water Supply Schematic	B4
1.4	Typical Water Demand Rates For RMOC	B5
1.5	Maximum Day In Summer: Water Demand Rates For RMOC (1991)	B5
3.1	RMOC's Network Schematic	B6
4.1	Consumption Data For Hurdman Bridge Branch	B7
4.2	Consumption Data For Billings Bridge Branch	B7
4.3	Consumption Data For Carlington Heights Branch	B8
4.4a	Consumption Data For Glen Cairn/Stittsville Branch	B9
4.4b	Consumption Data For Barrhaven Sub-Branch	B9
4.5	Example Of Level I Optimization Output (Glen Cairn/Stittsville Branch For A Typical Summer Night)	B10
4.6	Example Of Level I Linear Programming Formulation For "Optimizer" (Glen Cairn/Stittsville Branch For A Typical Summer Night)	B11
4.7	Example Of Level II Linear Programming Formulation For "Optimizer" (Glen Cairn/Stittsville Branch For A Typical Summer Night)	B12
5.1	Hurdman Bridge Branch Level I Optimization - Summer Night	B13

Figure | Page

5.2 Hurdman Bridge Branch Level I Optimization - Summer Day B14

5.3 Hurdman Bridge Branch Level I Optimization - Winter Night B15

5.4 Hurdman Bridge Branch Level I Optimization - Winter Day B16

5.5 Billings Bridge Branch Level I Optimization - Summer Night B17

5.6 Billings Bridge Branch Level I Optimization - Summer Day B18

5.7 Billings Bridge Branch Level I Optimization - Winter Night B19

5.8 Billings Bridge Branch Level I Optimization - Winter Day B20

5.9 Carlington Heights Branch Level I Optimization - Summer Night B21

5.10 Carlington Heights Branch Level I Optimization - Summer Day B22

5.11 Carlington Heights Branch Level I Optimization - Winter Night B23

5.12 Carlington Heights Branch Level I Optimization - Winter Day B24

5.13 Glen Cairn/Stittsville Branch Level I Optimization - Summer Night B25

5.14 Glen Cairn/Stittsville Branch Level I Optimization - Summer Day B26

5.15 Glen Cairn/Stittsville Branch Level I Optimization - Winter Night B27

5.16 Glen Cairn/Stittsville Branch Level I Optimization - Winter Day B28

5.17 Barrhaven Sub-Branch Level I Optimization - Summer Night B29

5.18 Barrhaven Sub-Branch Level I Optimization - Summer Day B30

5.19 Barrhaven Sub-Branch Level I Optimization - Winter Night B31

5.20 Barrhaven Sub-Branch Level I Optimization - Winter Day B32

5.21 Energy Costs For A Typical Summer Day With CH2W On Or Off B33

5.22 Energy Costs For A Typical Winter Day With CH2W On Or Off B33

Figure | Page

5.23 Glen Cairn/Stittsville Branch Level I Optimization - Summer Day With CH2W Offline B34

5.24 Glen Cairn/Stittsville Branch Level I Optimization - Winter Night With CH2W Offline B35

5.25 Glen Cairn/Stittsville Branch Level I Optimization - Winter Day With CH2W Offline B36

5.26 Carlington Heights Branch Level I Optimization - Summer Day With CH2W Offline B37

5.27 Carlington Heights Branch Level I Optimization - Winter Night With CH2W Offline B38

5.28 Carlington Heights Branch Level I Optimization - Winter Day With CH2W Offline B39

5.29 Glen Cairn/Stittsville Branch Energy Costs For Typical Summer And Winter Days B40

5.30 Glen Cairn/Stittsville Branch Energy Costs Per Unit Operating Volume For Typical Summer And Winter Days B40

5.31 Glen Cairn/Stittsville Branch Total Costs For A Typical Summer Day B41

5.32 Glen Cairn/Stittsville Branch Total Costs In An Hypothetical Case B41

5.33 Glen Cairn/Stittsville Branch Impact Of Increasing Demand B42

5.34 Glen Cairn/Stittsville Branch Increasing Demand With Increasing Operating Volume B42

5.35 Carlington Heights Branch: Impact Of Increasing Pipe Constraint - Summer B43

5.36 Carlington Heights Branch: Impact Of Increasing Hurdman Bridge R1E Reservoir Operating Volume And The Pipe Constraint - Summer B43

5.37 Carlington Heights Branch: Impact Of Increasing Billings Bridge R2C Reservoir Operating Volume And The Pipe Constraint - Summer B44

Figure | Page

5.38 Carlington Heights Branch: Impact Of Increasing Billings Bridge R2C Reservoir Operating Volume - Summer B44

5.39 Carlington Heights Branch: Impact Of Increasing Water Demand - Summer B45

GLOSSARY

Parameters

F_v ....fixed valve constraint on filling/emptying reservoir, ML/h

K .... maximum number of control intervals

M_n .... maximum number of pump combinations

Q_m^k .... pump flow rate, ML/h

R^k .... unit cost of electricity, $/kW.h

S^{end} .... final storage volume, ML

S^k .... storage volume at the end of control interval, ML

S^{k-1} .... storage volume at the start of control interval, ML

S^{max} .... maximum storage volume, ML

S^{min} .... minimum storage volume, ML

S^{start} .... initial storage volume, ML

T^k .... duration of the control interval, hours

T_v .... effective time when the fixed valve to/from reservoir is open at F_v, hours

U_m^k .... power consumption, kW.h/ML

V^k .... consumer demand, ML

X_m^k .... pumping time, hours

Superscripts and Subscripts

k .... control interval number

m .... pump combination number

v .... refers to 'valve'

Abbreviations

BAR .... Barrhaven

BB2C .... Billings Bridge pumping station in zone 2C

BHPS .... Barrhaven pumping station in zone BAR

BR1W .... Britannia pumping station to zone 1W

BR2W .... Britannia pumping station to zone 2W

C .... Central

CH2W .... Carlington Heights pumping station to zone 2W

DP .... Dynamic Programming

E .... East

FS1W .... Fleet Street pumping station to zone 1W

GP .... Goal Programming

HB1E .... Hurdman Bridge pumping station in zone 1E

LI1W .... Lemieux Island pumping station to zone 1W

LP .... Linear Programming

MOLP .... Multiobjective Linear Programming

MTL .... Montréal Road consumption zone

NLP .... Nonlinear Programming

OM .... Optimization Model

RBAR .... Reservoir code name in zone BAR

RMOC .... Regional Municipality of Ottawa-Carleton

R1E .... Reservoir code name in zone 1E

R1W .... Reservoir code name in zone 1W

R2C .... Reservoir code name in zone 2C

R2W .... Reservoir code name in zone 2W

SGL .... South Gloucester consumption zone

W .... West

WPP .... Water Purification Plant

CHAPTER 1

INTRODUCTION

With advances in computer technology, it is now possible to optimize the operations of water supply distribution systems i.e. reservoir releases and pumping schedules. These operations are increasingly complex due to rising water demand, aging systems, the addition of new sources of varying water quality or the lack of new reservoir sites available. It is important that water demand is met without the treatment plants and/or power plants being stressed to capacity limits. System reliability is also important for adequate fire protection and system pressures.

In addition to these concerns, energy conservation has become a top priority since nearly 7% of the electricity produced in the United States is consumed by municipal water utilities (Jamieson et al., 1993), mainly for pumping water. Increasing the efficiency of individual pumps has only little impact, therefore system or operating efficiency has to be increased through the use of optimization models with the ultimate goal of reducing operating costs. Low-cost, more reliable computer technology is now available to solve the problem of water supply operations optimization.

1.1 CHARACTERISTICS OF OPERATIONS OPTIMIZATION MODELS

Optimization models (OMs) for water supply system operations are designed primarily to reduce operating costs. The literature review (Chapter 2) will summarize some important recent contributions concerning the development of these models.

In general, OMs are part of a much wider plan towards more increased automation of water supply systems. The building blocks towards full automation include: improved demand forecasting by real-time telemetry and use of time series analysis; better hydraulic simulation with the development of network models that use data from telemetry; treatment process optimization within the water purification plants (WPPs); operations optimization, which we will discuss in detail; cost optimization of all components; and finally, telecontrol. Therefore, with increased precision in determining important parameters (especially flows and pressures) anywhere in the system and the means to communicate these data to a control centre, better decisions can be made in the operations model (which controls pumps and reservoir releases), to achieve the minimum cost.

To justify implementing such sophisticated automated systems, a significant reduction in operating costs must be achieved from the 'operations' OM. The literature indicates possible savings of 5 to 10% from improved pump scheduling and up to 20% with improved demand forecasting (Crawley and Dandy, 1993; Jamieson et al., 1993; Ormsbee et al., 1989; Tarquin and Dowdy, 1989; and Anonymous, 1988b). The principal goal of our study is to identify, through application of an 'optimization' model, the potential savings from improved pump scheduling for the Regional Municipality of Ottawa-Carleton's (RMOC) water supply system. The second goal is to study the impact of different water management alternatives on energy costs, alternatives such as: (i) increasing storage capacity; (ii) reevaluating the safety coefficients on the minimum storage capacity needed; (iii) increasing pipe sizes; (iv) increasing treatment capacity; and (v) increasing water demand; for the Region's water distribution system. Although it is based on historical data instead of a demand forecasting module and a hydraulic simulator, and although it is not designed for real-time, our model is designed to provide answers to some of RMOC's water supply efficiency concerns.

1.2 THE REGIONAL MUNICIPALITY OF OTTAWA-CARLETON (RMOC)

The Region includes the municipalities of Ottawa, Vanier, Rockcliffe Park, Cumberland, Gloucester, Goulbourn, Kanata, Nepean, Osgoode, Rideau and West Carleton (RMOC, 1993). These are shown on a map of the Region presented in Figure 1.1a. The population and area of each municipality are listed in Table 1.1. RMOC's total population as of 1991 was 678 150 residents and the total area was 275 698 hectares.

Figure 1.1b shows the four distinct patterns of regional growth, namely: the Inner Area, Urban areas inside the Greenbelt, Urban areas outside the Greenbelt and the Rural areas. The Greenbelt was established in 1961 to limit urban expansion and to preserve natural land as forests, marshes and swamps. The urban areas outside the belt have developed their own identities due to the physical barrier, leading to three independent urban centres: West (Kanata), East (Orléans) and South (Barrhaven) [refer to Figure 1.1b]. There are also three smaller sub-areas that have a distinct character: Stittsville, west of Kanata urban centre; Bell's Corners, represented in the figure as a white area within the Greenbelt in Nepean (just east of Kanata urban centre); and Blackburn Hamlet, represented as a white area within the Greenbelt in Gloucester (just west of Orléans urban centre) (RMOC, 1994; RMOC, 1993). The land uses in RMOC are approximately as follows: 8% wetland; 35% wooded; 15% grass, meadows and old farm fields; 8% urbanized; 4% villages and other rural development; and the last 30% is actively farmed. The urban land uses are shown in Figure 1.2 (RMOC, 1994).

Politically, RMOC was created in 1969 as the upper level of a two-level municipal government structure led by the Regional Council which is formed by 18 directly elected councilors and the elected Chair (new structure as of November 1994). RMOC's responsibilities include: regional planning; water purification and distribution; wastewater treatment and major sanitary sewers; stormwater management; disposal of solid waste; regional roads; transit (OC Transpo); social services (welfare, daycare); community health programs; and homes for the aged. Under Bill 77, its responsibilities will be extended to include: policing in Ottawa, Vanier, Nepean and Gloucester; waste collection; and other economic development powers (RMOC, 1994).

1.2.1 RMOC'S Water Supply System

The first piped water distribution system in Ottawa was installed in 1874 mainly for fire protection following the Great Fire of 1870. Before that, the 26 000 citizens of Ottawa had their water delivered by horse-drawn wagons. The water was taken raw from the Ottawa River at the foot of St. Patrick Street. An 1888 water quality analysis noted the 'brownish' color but the water was declared 'fit to drink'. Outside the downtown core, water was drawn from wells (RMOC, 1992).

Potable water is now supplied to the RMOC's central supply system through the Lemieux Island and Britannia Water Purification Plants (WPPs), both situated along the Ottawa River. These two plants, which are designed to provide a total of 640 megalitres per day (ML/d) in the summer and 560 ML/d in the winter to the distribution system, are run on electrical and/or diesel power. RMOC's water supply system is represented schematically in Figure 1.3.

The Region's water supply is divided into East, Central and West (E, C, W) and is further subdivided into six major water pressure zones as follows: 1W, 1E, 2W, 2C, 2E and 3W. These correspond to water demand from consumers illustrated by triangles in Figure 1.3 (at this point 1E and 2E are grouped together under C1E). There are also four minor pressure zones, namely: Barrhaven (CBAR), South Gloucester (SG), Meadowlands (MDL) and Montréal Road (Mtl Rd). "EMR" stands for Energy, Mines and Resources Canada situated in the west end. The first letter "C" in "C1W, C1E, C2C, C2W, CBAR" indicates that these are important water Consumption zones used later in the model.

Primary storage capacity is provided by four main service reservoirs illustrated by cylinders in Figure 1.3: Orléans (81.8 ML) in pressure zone 1E; Carlington Heights (109.1 ML) in zone 1W; Glen Cairn (34.1 ML) in zone 2W; and Barrhaven (19.5 ML) in zone 2W . Three elevated tanks ('elevated tank' icon in Figure 1.3) make up secondary storage as follows: "Innes Road" (4.6 ML) on Innes Road, at the city limits of Gloucester and Cumberland (zone 2E); "Ottawa South" (3.4 ML) on Alta Vista Drive near Randall Avenue, in the City of Ottawa (zone 2C); and "Stittsville" (4.6 ML) at Old Highway 7 and Carp Road, in Stittsville (zone 3W). Other storage comes from one storage tank illustrated by a square in Figure 1.3: "Montréal Road" (3.3 ML) at Montréal Road near Burma Road in the City of Ottawa (zone 1E).

Pumping from the water purification plants (WPPs) to the distribution system is accomplished through four stations, two in each WPP: Britannia WPP has BR2W and BR1W pumping stations (i.e. pumping water to pressure zone 2W or 1W); and Lemieux Island WPP has LI1W and FS1W (FS meaning Fleet Street, both pumping to pressure zone 1W). Pumping stations are illustrated as circles in Figure 1.3. The WPPs' pumping stations appear as BR2W, BR1W, LI1W and FS1W in the figure. Fleet Street runs turbine pumps with power provided from the Ottawa River hydraulic head differential, since the pumping station is situated on ground level lower than the water surface elevation.

Other smaller stations (also illustrated as circles in Figure 1.3) pump water to different zones in the distribution system, namely: HBPS (Hurdman Bridge pumping station) pumps to zone 1E; BBPS (Billing Bridge pumping station) pumps to zone 2C; CHPS (Carlington Heights pumping station) pumps from zone 1W to 2W; BHPS (Barrhaven pumping station) pumps to Barrhaven water demand zone; GCPS (Glen Cairn pumping station) pumps to zone 3W; EMR-PS (Energy, Mines and Resources Canada) pumps to EMR water demand zone; MDL-PS (Meadowlands pumping station) pumps to MDL water demand zone; SG-PS (South Gloucester pumping station) pumps to SG water demand zone; MTL-PS (Montréal Road pumping station) pumps to Mtl Rd water demand zone; and finally, three smaller pumping stations (i.e. Orléans, Queenswood South) pump to zones 1E and 2E.

The RMOC system supplies approximately 400 ML/d on a typical summer day and 325 ML/d on a typical winter day. For a given household, this represents about 1 000 litres daily or 270 litres per person per day. On average, 45% of water used in the house is for flushing toilets; 30% for showering; 20% for laundry and dishes; and only 5% for cooking meals (RMOC, 1994; RMOC, 1992). Water demand in the Region follows the pattern in Figure 1.4. There are two peaks. As people start to wake up at 06:00 hours, water demand rises steadily until 08:00 hours (when the majority of people leave for work). Between 08:00 hours and 11:00 hours, demand continues to rise (but at a slower rate), to reach the day peak around 11:00 hours. After 11:00 hours, demand decreases slowly only to rise again as people return home around 16:00 hours, to reach the evening peak at 20:00 hours. Demand then decreases through the night until the next morning. The same pattern applies to winter water demand but the afore mentioned peaks are not as sharp.

1.2.2 Ottawa Hydro's Rate Structure

Canada is the country with the highest per capita energy use in the world mainly due to the cold climate and the long distances we have to travel, but also because of the North American lifestyle (consumption = waste). The first hydroelectric power plant in Ottawa was at Chaudière Falls. It is still in operation but currently it produces less than 1% of the peak load. As of January 1992, peak electricity demand in the Region was 1 800 megawatts (MW). Electricity produced locally amounts to only 6% of total demand while another 20% comes from hydroelectric plants in eastern Ontario (Arnprior, Calabogie, Burnstown). The remainder is supplied by oil-fired facilities at Cornwall and by the Lennox plant near Kingston. Occasionally, power may also be supplied from the nuclear energy plants at Pickering and Darlington, depending on province-wide loads (RMOC, 1992).

Ottawa Hydro purchases electricity from Ontario Hydro and supplies it to users that are billed according to demand in kilowatts (kW) and consumption in kilowatt-hours (kW.h). Both Lemieux Island and Britannia water purification plants are in the 2000-5000 kW demand bracket. Because of this, the WPPs are considered 'large' users (>2000 kW) and therefore they are subject to Ottawa Hydro's "General Service Time-Of-Use" electricity tariff (specific to the 2000-5000 kW demand bracket).

The electricity tariff structure as used in the model developed (Table 1.2) has three main advantages: (i) the rates during '*off-peak*' hours are lower than during '*peak*' hours (07:00-23:00 weekdays, except for statutory holidays); (ii) the rates during summer (April to September) are lower than during winter (October to March); (iii) there are savings of 1/3 off those rates under the '*restricted hours*' agreement. This is a major incentive offered by Ottawa Hydro for 'peak shaving' (i.e. to keep electricity demand below a predetermined peak value). From historical data, Ottawa Hydro determines hours of the week when it is the most likely to reach peak demand during each month. This becomes the *restricted hours* schedule. During those hours, whenever Ottawa Hydro management forecasts that the predetermined peak value might be attained, they ask 'large' users to stop using hydro power. For Lemieux Island and Britannia WPPs, this means switching to diesel power for pumping purposes. If a user cannot meet this schedule, it can be subject to a penalty for contributing to the electricity demand peak for that month. Table 1.3 presents the *restricted hours* schedule throughout the year. During winter (October to March), there are two blocks of *restricted hours*: morning and evening; while during summer, there is a single block: most of the work day.

The biggest challenge for RMOC's water managers is to meet consumers' water demand during the *restricted hours* with a minimum need for electrical pumps and by doing so, avoiding penalty charges built into the Hydro agreement. Therefore, utilizing the maximum amount of water stored in the service reservoirs during the day to meet the demand and filling the reservoirs at night (when the electricity is cheapest) can reduce electricity costs significantly.

1.2.3 Water And Electricity Management

An important consideration in water supply system management is the respective peak demand patterns for electricity and water. The peak demand pattern for water from the WPPs differs from that for electricity from Ottawa Hydro. Because of lawn and garden watering (amongst other things), peak demand for water is highest during the evening of the warmest and driest days of summer (Figure 1.5). Peak water demand corresponds to peak electricity usage for the WPPs. Ottawa Hydro has two peak electricity demands. The largest occurs during the coldest days of winter mainly because of heating requirements and the second is during the hot summer days due to air conditioning loading. Therefore, in regards to avoiding penalty, the summer period is more critical.

Optimizing both pump scheduling and reservoir releases is an effective way to fully profit from this billing structure. By simplifying the water supply system schematic and studying the parameters involved, it is clear that linear programming is an option for the optimization of the electricity cost function. In developing a model for RMOC's water distribution system, there was concern about using a computer environment that is familiar to water managers instead of advanced programming code that would require extensive training. Too many models are designed but never used. Linear programming is used for this first attempt at quantifying the potential energy savings for RMOC but more sophisticated modelling approaches are available to obtain more detailed results that could lead to real-time applications.

CHAPTER 2

LITERATURE REVIEW

2.1 OPERATIONS OPTIMIZATION IN WATER SUPPLY DISTRIBUTION SYSTEMS

The pump scheduling problem associated with municipal water supply has received much attention in the last ten years due to advances in computer technology. This literature review concentrates on what has been accomplished in recent years, both in the operations optimization of water supply distribution systems and in similar fields of water resources. The first three sections outline the general problem, present some specific examples and discuss mathematical considerations. The last two sections briefly review research done on other aspects of water supply operations optimization and other types of optimization in water supply distribution networks.

2.1.1 General Problem

Pumping of water from the WPPs represents the most significant use of energy at the plants. Optimization of pump scheduling is therefore one of the principal means of reducing energy costs. The following recent studies confirm that reducing energy cost is a top priority:

Jowitt and Germanopoulos' (1992) method applied linear programming (LP) to determine the optimal pumping schedule over a 24-hour period. Their program was implemented in the Northern Division of Thames Water Authority, Buckinghamshire, England, and resulted in significant reductions in pumping costs.

Forzini (1991) reported the work done to automate the Méry-sur-Oise plant in suburban Paris, France. The optimized pumping program was developed to satisfy three main objectives: (i) optimization of energy costs; (ii) safeguard of water quality; and (iii) safety of supply to consumers. The program consists of two main modules: the forecasting module and the pumping management module, which is subdivided into the hydraulic, mechanical and power units. The hydraulic unit deals mainly with the different pump combinations possible under maximum flow rate constraints. The mechanical unit is designed to select the 'best' combination, both mechanically and electrically. The power management unit checks the power consumption of the chosen combination versus the authorized design power. The ultimate goal is to upgrade the level of automation of the water supply system from a few automated reservoir level switches and timing system to a fully automated pilot system.

Zessler and Shamir (1989) used progressive optimality (PO), an iterative dynamic programming (DP) method to find an optimal pump operations schedule for the Ein Ziv system, in Israel. The regional system is divided into subsystems of one pumping station between two reservoirs. A full 24-hour optimization run written in Pascal on a IBM PC/XT took 10 to 15 minutes to reach a solution.

In the United States, Ormsbee and Chase (1988) tackled the optimal pump operations problem by developing an optimal tank trajectory for each reservoir in the system and an optimal operating policy to achieve those trajectories. The optimal trajectory represents the minimum operating cost. Ormsbee et al. (1989) used the above methodology based on DP for water distribution systems with a single dominant storage reservoir and multiple pump stations. A case study in Washington D. C. and its vicinity projected savings of approximately 6.7% annually. Chase and Ormsbee (1990) differentiated between two approaches in the development of computer models for optimal operations: macroscopic or microscopic. The macroscopic approach uses database and regression curves to approximate the hydraulic system. It is a quicker way to obtain a solution and therefore can be used for real-time control although it is not adaptable between different water supply systems. The microscopic approach uses simulation models coupled with optimization packages to solve the operations problem. It is robust, accurate and adaptable but it can be time-consuming and therefore violate real-time requirements. Chase and Ormsbee (1991) expanded on their research with nonlinear programming (NLP). To formulate the main problem, they combined the control variable sub-problem (optimal operating policy) with the pump operations sub-problem. The main decision variable becomes the pump operating times.

Brion and Mays (1991) coupled the KYPIPE hydraulic simulator with a large-scale NLP scheme solved by a generalized reduced gradient code: GRG2 (Lasdon and Waren, 1982). Preliminary results from the city of Austin, Texas, projected a 17.3% reduction from the actual operating costs. The major drawback is that the model is too time-consuming to be used in real-time.

Jamieson et al. (1993) developed a knowledge-based energy management system (KBEMS). They sacrificed 'pure' optimality for a good and efficient operating plan that incorporates operators' knowledge and therefore offers great flexibility. The goal was to reduce high-service pump operating costs by implementing network telemetry. Computer control was applied to three main areas: real-time data acquisition and management of elevated storage levels, network pressures and flows; water demand forecasting by time series and operator's knowledge; and pump scheduling by DP. Preliminary results gave reductions of 17.8% in electricity cost for the month of September 1989 and 20.9% for December of the same year, for the city of Arlington, Texas.

In Australia, Crawley and Dandy (1993) developed a method based on linear goal programming to identify optimal operating policies in metropolitan Adelaide. One of their major concerns was to ensure system reliability: therefore an important constraint in the mathematical formulation of the problem was the minimum-target storage levels for each reservoir. Savings on the total pumping costs are expected to be between 5% and 10%, and up to 20% with improving demand forecasting.

2.1.2 Examples

Apart from the ones mentioned above, other examples of the optimization of water supply system operations appear in the literature in recent years. Flemal et al. (1988) highlighted the method and philosophy behind the optimal management of the Charleroi water distribution system in Belgium. Their advanced system is based on real-time data acquisitions and telecontrol.

The Essex Water Company in England estimated the electricity cost savings at about 10% since using 'Options', their pump scheduling model (Anonymous, 1988b). They used four main features to enhanced water management: data collection, network simulation, remote control and pump performance tests (head/flow and power/flow). The savings were obtained by changing the management of pumps, of the different sources and by a better use of the electricity tariffs. It was also reported that the construction of the London Water Ring Main will help to reduce pumping costs by establishing a link between the treatment works and demand in central and north east London (Anonymous, 1988a). Information from sensors is telemetered to control centres where they are saved in extensive databases and processed for optimization. The optimization model used is based on GINAS V, developed by Leicester Polytechnic.

Lastly, Renalías et al. (1992) described the efforts of 'Sociedad General de Aguas de Barcelona' towards automatic exploitation of Barcelona water supply system. The control system in place is based on telecontrol for the metropolitan area of Barcelona which comprises 28 municipalities for a total of 3.3 million people. The main criteria of decision are the energy costs, service quality and continuity.

2.1.3 Mathematical Considerations

Ulanicki and Orr (1990) presented a theory for the optimization of water supply and distribution systems. Their paper can serve as a guideline for the mathematical formulation of the problem and its solution. The mixed-integer nonlinear problem is transformed into a two-level 'time distribution function'. The upper-level defines the storage policy while the lower-level solves for the average flows under pressure head constraints by LP. An example for a major city in the U.K. (unnamed) is presented where savings of roughly 7% of the total operating costs were achieved. Ulanicki (1991) extended this concept by adding spatial decomposition to divide the water system into sub-systems which provide the basic structure to solve the scheduling problem. These two concepts are used with a three-layered (reservoir dynamics, nonlinear static hydraulics and transitional phenomena in pipes) 'water supply and distribution network' model to combine simulations and optimization in a single package.

Edmunds and Bard (1990) introduced a new decomposition technique to solve large-scale optimal control problems. Their model uses 'time-axis' decomposition to divide the larger problem into a series of sub-problems that are easy to solve. The mathematics are clearly formulated and are illustrated with the water resources management problem of scheduling the three-reservoir hydroelectric power system. Brdys (1992) examined the problem of determining optimal control schedules for a class of cascade water supply systems with only fixed speed pumps. The complex nature of the problem comes from the fact that there are both discrete (e.g. *on/off*) and continuous (e.g. time) variables. Again, the complex mathematical formulation is thoroughly presented and many examples are given.

Chen and Coulbeck (1991) were concerned with water supply systems with a mixture of fixed- and variable-speed pumps. The large-scale dynamic linear problem can be solved by using time of pumping instead of pump discharge as a decision variable. By discretizing the speed range of the variable speed pumps, only discrete parameters need to be assessed. The model was fully tested for the Nurton/Bushbury zone in the city of Wolverhampton, U.K.

2.1.4 Other Aspects Of Water Supply Operations Optimization

Many other aspects of the optimization of water supply systems are studied in Europe and in the United States. In Europe, Piqueiro et al. (1991) showed that the reduction of safety coefficients, by reconsidering the use of maximum daily demand as a design criterion and using simple intermittent pumping operations, are two efficient ways to reduce costs. Hartley and Powell (1991) and Jowitt and Xu (1991) investigated the use of time series analysis (ARIMA) for demand forecasting. Jarrige et al. (1991) discussed the role of information technology needed for improved management of fully automated water supply systems. Jack et al. (1991) incorporated thermodynamic measurement of pump efficiency into the pump scheduling module in view of full automation.

In the U.S., Tarquin and Dowdy (1989) were also concerned with pump efficiency in regards to selecting the best possible pump combination. For different head-discharge conditions, the most effective pump combination in terms of cost was selected using pump curves and system head curves. Field tests to determine the actual characteristics and efficiency of the pumps permitted energy cost savings of around 9.2% in the city of El Paso, Texas.

2.1.5 Other Types Of Optimization In Water Supply Distribution Networks

Sabet and Helweg (1989) investigated the impact of constructing peaking storage tanks to reduce pumping costs associated with water supply systems in municipalities where the cost of electricity varies according to the time of day (peak and off-peak). Using a DP optimization model, they were able to produce an optimal pump schedule and find an optimal peaking storage tank size.

Ostfeld and Shamir (1993b,c) worked on the optimal operation of multiquality networks both under steady-state and unsteady conditions. The objective function was to minimize the total cost with constraints on the quantity, quality and pressure. It was solved with GAMS for: General Algebraic Modeling System (Brooke et al., 1988), and MINOS for: Mathematical In-core Nonlinear Optimization System (Murtagh and Saunders, 1982). The model, based on a projected augmented Lagrangian algorithm, is a policy model (creates guidelines) and therefore cannot be used for real-time.

Diba et al. (1993) used LP to design a water supply distribution system planning model for the Metropolitan Water District of Southern California. They formulated the problem using a multiobjective approach and allowing for the use of preferential weights for the different components. The model is used to evaluate many aspects of water supply system planning and management and to estimate a system's reliability.

Duan et al. (1990) developed a reliability-based optimization model for the design of pipe networks, pumping systems and optimal operation of the pumps. The problem is presented as a large mixed-integer nonlinear problem which is solved using a generalized reduced gradient code: GRG2 (Lasdon and Waren, 1982). The reliability-based procedure considers hydraulic failure in the network and mechanical failure of the pumping system.

Ostfeld and Shamir (1993a) also incorporated reliability in the optimal design of water distribution networks. They highlighted the problem of defining reliability measures that are relevant and that can be used readily in optimization models. Kabir (1990) took advantage of *Lotus 1-2-3*'s spreadsheet capabilities to find the optimal design of water transmission mains, to perform a financial evaluation of pipe lines and pump stations and also to analyze the sensitivity of the design to changes in the input parameters. He did not however use some of the more advanced features that this software has to offer (e.g. optimization tools).

2.2 OPTIMIZATION IN WATER RESOURCES

The first two sections will show recent research in two peripheral aspects of water supply systems, namely: hydrological reservoirs and water/waste treatment, which share similar concern for the development of optimization models to control operations and reduce costs. Again, there is no consensus in the type of mathematical programming used to solve the different optimization problems; more advanced studies report the work done towards full automation. In the third section, we will look at similar work done in the hydroelectric industry.

2.2.1 Water Reservoirs

Dallas Water Utilities (DWU) designed a mathematical computer model to optimize the operations of a multiple reservoir supply system. The model has three basic modules: monthly mass-balance computations on each reservoir, a decision-making routine and the calculation of operating costs. McCarthy (1990) reported that the DWU model has been used successfully to find the right balance between supplying the demand in years of drought while minimizing operational costs in the long run.

Reznicek et al. (1991) used a goal programming (GP) approach to optimize the short-term operation of a single multipurpose reservoir. The objective was to model the complex real-time reservoir operations. Their original approach was with LP but GP provided a more efficient way to solve the problem because less data is required and the problem can be more simply formulated.

Five different GP techniques and also multiobjective linear programming (MOLP) were compared by Loganathan and Bhattacharya (1990) for modelling reservoir operations. The authors discussed the characteristics of the five GP schemes ('preemptive', 'weighted', 'min-max', 'fuzzy' and 'interval') and of MOLP and what should govern the decision to implement them. They illustrated their point with a case study of the Green River basin in Kentucky (U.S.).

Wurbs (1993) has inventoried the major models used for the evaluation of reservoir operations. He distinguishes between simulation and optimization models and compares them from a general overview perspective, highlighting practical considerations. His paper can serve as a reference for water managers and engineers in selecting an existing model for reservoir system analysis. Much attention has been given to multiobjective decision making in recent years.

Hipel (1992) gave the example of the Three Gorges dam on the Yangtze river in the Republic of China where numerous objectives were pursued, including 'social', 'economical', 'financial', 'environmental', etc. He also compared different methods used in water resources management and he presented a table of the major contributions in this field that sprung from operational research.

2.2.2 Water And Waste Treatment

In regards to reducing costs, optimization models are a priority in the water and waste treatment industries all over the world. In the Republic of China, Wu and Chu (1991) designed a model based on NLP to minimize the costs of the design and operation of a water treatment plant in Taiwan. The decision variables were the chlorine and alum feed rates as well as the design specifications for the mixing, flocculation, sedimentation and filter operations. The model identified the most cost-effective basin sizes and feed rates resulting in annual savings of about 1 000 000 NT Dollars (36 900 U.S. Dollars in 1991).

In India, Mhaisalkar et al. (1993) developed a DP model for functional and minimal-cost design of the Kerala Water Authority treatment plant at Trivandrum. Since it is a measure of the effectiveness of the various stages of treatment, suspended solids was chosen as the only state parameter in the formulation of the problem. The optimal design from the model is different from conventional designs mainly because of values obtained for surface overflow rates in the clarifier and filtration rate.

In the United States, Ciric and Huchette (1993) are concerned with the multiobjective challenge of optimizing chemical processes in the waste treatment industry. The goal is to minimize waste production while maximizing profits. The problem is modeled as a multiobjective mixed integer nonlinear programming problem (MOMINLP). Their method is based on the fundamental relationship between sensitivity analysis and multiobjective optimization.

In France, where the water industry is most advanced, full automation of water treatment stations is described by Weber (1991). Advances in telecontrol and computer technology permit real-time operations of such schemes. This paper clearly illustrates the hierarchical levels and redundancy needed for a reliable telecontrol system and all the possible areas of automation in the water industry.

2.2.3 Hydroelectric Systems

The hydroelectric industry has developed many optimization models of their own, especially for the scheduling of its operations. Research in this field is ongoing worldwide. In China, Zhang et al. (1991) used DP to achieve optimal real-time control of hydroelectric power plant. Their work is quite similar to the pump scheduling problem considered in this study. They used a two-level (spatial and temporal) optimization technique to solve the dynamic one. The result is a 'daily-hourly' schedule. They also performed a sensitivity analysis to assess the impact of errors on the characteristic curves of the hydroelectric units and on demand forecasting. Even with small deviations in those parameters, significant water consumption savings were achieved.

In Malaysia, Rashid and Nor (1991) reported an efficient method for optimal scheduling of fixed-head hydro and thermal plants using Lagrange multipliers. Their main concern was to minimize the fuel cost of the thermal plants under generation limits constraints as well as available water and energy balance constraints.

In Brazil, Ohishi et al. (1991) designed a model for short-term hydrothermal scheduling primarily for hydro systems. They used simulation coupled with an optimal DC (direct current) load flow model, taking care of hydraulic, electrical and transmission aspects of those complex systems. In Columbia, Moslehi et al. (1991) tackled the problem of optimizing the short-term operation of a multi-plant cogeneration system in a large industrial complex. The objective function was to minimize the overall cost of all fuels and makeup water used during the control interval (1 to 24 hours). The constraints were defined by electric and steam system requirements. The output was a schedule of electricity and steam production.

In Iceland, Hreinsson (1988) worked on the optimal short-term operation of a purely hydroelectric system that he defined as a mixed integer nonlinear problem. His goal was to produce an hourly schedule of power production that would be optimal in reducing losses in turbines and waterways. To achieve a solution, he developed an algorithm using LP in two stages, which resulted in large savings in water usage from large seasonal reservoirs of the Icelandic Power system. The ultimate goal is to integrate the model in a computerized control centre. In Sweden, Gustafsson (1993) studied two different methods of finding optimal solutions to the scheduling problem in 'Combined Heat and Power' networks using LP.

In North America, Christensen et al. (1991) developed a model for solving the load-following scheduling problem for large-scale hydroelectric systems. The objective is to maximize power generation with the most uniform surplus power. The technique used is the minimum norm formulation of functional analysis. They successfully tested the model with the Bonneville Power Administration hydroelectric system, considered one of the largest hydro systems in the world. Grahovac and Simonovic (1990) designed an expert system for budget preparation and optimal operation of an interconnected power utility. The Energy Management and Maintenance Analysis computer program is based on LP and its main objective is meeting the loads while minimizing costs and maximizing benefits. Barbour et al. (1989) completed a joint planning study on the economic potential of pumped storage in Colorado. They used the Electric Generation Expansion Analysis System developed by the Electric Power Research Institute to assess the impact of pumped storage. Different alternatives can be compared in view of efficient use of present resources and future needs.

CHAPTER 3

THEORY

As seen from the literature review, there is no consensus on the preferred type of mathematical programming for solving the 'pump-scheduling' problem. The most common are: linear programming (LP), nonlinear programming (NLP), dynamic programming (DP), goal programming (GP) and multiobjective programming (MOP). Actually, pump scheduling and reservoir releases problems are implicitly all of the above: multiobjective, since the goals are to minimize operating costs as well as maximizing security of supply and system reliability; goal, since there are target reservoir storage volumes to be attained at the end (or start) of a time period (e.g. full reservoirs at 07:00 hours); dynamic, because the problem evolves with time; nonlinear, because the cost function and some constraints can be formulated as nonlinear equations (e.g. quadratic); and finally linear, because by time and spatial decomposition, the problem can be expressed with linear equations.

Considering all these aspects and the necessity of finding an efficient solution to the problem, LP was chosen as the most well-defined type of mathematical programming and therefore the easiest to solve if the objective function and the constraints can be clearly formulated. The next section will describe the LP approach as applied to RMOC's water supply system. There are two levels of optimization involved: Level I is for solving for pumping times, and Level II for creating the pump schedules. The LP formulation presented is a general form of the objective function and constraints based on the basic structure of one pumping station with many pumps, supplying water to one water demand zone with one reservoir. Some modifications are necessary where there are more than one pumping station and/or more than one reservoir.

3.1 THE LINEAR PROGRAMMING PROBLEM

As mentioned above, spatial and time decomposition are essential if one wants to solve the pump scheduling problem using LP. Spatial decomposition (Ulanicki, 1991) is performed by creating a network schematic (Figure 3.1) that is a simplified version of the water supply system schematic (Figure 1.3). Minor consumer demand zones are grouped with major demand zones and the same is done with the reservoirs. Code names are assigned for clarity. Two major branches are identified: Carlington Heights (zone 1W) and Glen Cairn/Stittsville (zone 2W), which includes the Barrhaven (zone BAR) sub-branch. There are also two minor branches: Hurdman Bridge (zone 1E) and Billings Bridge (zone 2C). A full description of these branches can be found in Chapter 4. Each minor branch can be solved independently and the results are incorporated into the major branches that are in turn solved.

'Time-axis' decomposition (Edmunds and Bard, 1990) is used to transform the continuous variable time into discrete intervals called time steps. The optimization period of 24 hours is subdivided into K control intervals according to Ottawa Hydro's electricity rate structure, in this case K=2, namely: night (k = 1; *off-peak*) and day (k = 2; *peak*). The *restricted hours* are being considered when creating the pump schedule. All parameters involved have to be characterized as either integer (*on/off* pump status), discrete (pump combinations), or continuous (flow, discharge) variables and careful transformations have to be applied to obtain a homogeneous formulation of the problem. The same holds true for linear and nonlinear variables. Simplification is required in some instances: continuous variables are broken down into one value for each one-hour period.

All the necessary data was provided by RMOC from the water supply system's historical data. These were used to approximate the hydraulic performance of the system. Therefore, according to Chase and Ormsbee (1990), the approach can be categorized as 'macroscopic'. Some of the data is exact (water consumption, reservoir data) but some is estimated (power consumption) from past years' data adjusted for present year from observed trends in the historical data. Ultimately, the model developed will need to be calibrated if comparison with actual operation is required.

3.1.1 Level I Optimization - Solving For Pumping Times

A major assumption in defining the linear programming problem is that the network under consideration is correctly designed; i.e. the hydraulic characteristics of the network allow for acceptable internal pressures and/or flows under normal reservoir operations (Jowitt and Germanopoulos, 1992). This holds true for RMOC's network which has been supplying water successfully for many years. The basic structure of a branch consists of a pumping station, a reservoir and a consumer demand zone. This structure provides the basis for the mathematical formulation of the linear programming problem. Adapted from Jowitt and Germanopoulos (1992), the **electricity cost function** over control interval k (k = 1 and 2), for pumping water *at a particular pumping station,* becomes:

$$MIN\left[R^k \times \sum_{m=1}^{Mn} (X^k_m\, Q^k_m\, U^k_m)\right] \tag{3.1}$$

where X_m^k = pumping time for pump combination m (hours);

Q_m^k = flow rate for pump combination m (ML/h);

R^k = unit cost of electricity ($/kW.h);

U_m^k = power consumption factor for pump combination m (kW.h/ML);

M_n = maximum number of pump combinations;

For each pump combination (m = 1, ..., M_n) the flow rate (Q_m^k) is taken as the sum of the capacities of each pump in parallel. The unit cost of electricity (R^k) is given by Ottawa Hydro's rate structure. There are three different rate structures: (i) Ottawa Hydro's 'General Time-Of-Use' rates for the WPPs' pumping stations (in the 2000-5000 kW demand bracket) where a discount of 1/3 *off* the rates is in effect due to the agreement with Ottawa Hydro (*restriction* schedule); (ii) Ottawa Hydro's 'General Service' for the minor pumping stations in Ottawa; and (iii) City of Nepean's rates for the minor pumping station situated in Nepean (Barrhaven pumping station). Power consumption factor (U_m^k) is obtained from the pumps' electrical consumption divided by the rated discharge of the pump. At the WPPs, power used for water treatment is added on to take into account the higher cost of treatment for Lemieux (110 kW.h/ML) compared to Britannia (80 kW.h/ML). These estimates were provided by RMOC from records of total power consumption for pumping and treatment. There is some concern that the value for Lemieux Island treatment might be too high (personal communications with André Proulx, RMOC's Director, Water Division).

It should be noted that in RMOC's case, pipe sizes are more constraining than the WPPs' and other smaller stations' pumping capacity. The only exception is at Lemieux Island WPP, where the treatment capacity is the limiting factor used for selecting the possible pump combinations. Elsewhere, pipe size restrictions are used to limit the number of possible pump combinations. The pumping times (X_m^k) for each pump combination are the unknowns determined by the 'Optimizer' tool within *Borland's* Quattro Pro version 5.00 for *Microsoft* Windows, which is designed to solve LP schemes.

The **constraints** *at one particular pumping station* are:

a) <u>Duration of pumping within control interval k</u>:

$\Sigma_{m=1}^{Mn} (X_m^k) = T^k$ for the filling operation (k = 1) (3.2a)

$\Sigma_{m=1}^{Mn} (X_m^k) \leq T^k$ for the emptying operation (k = 2) (3.2b)

where T^k = duration of the control interval (hours);

During the *off-peak* period (k = 1), water is pumped into the reservoirs only (filling operation). Therefore, water has to be pumped during the entire duration of the control interval to meet consumer demand at the same time (Equation 3.2a). During the *peak* period (k = 2), water is pumped and/or drawn from the reservoirs (emptying operation). The pumping time can be less than the duration of the control interval because consumer demand can be met from reservoir releases (Equation 3.2b).

b) Minimum pumping time:

$X_m^k \geq 1$ for smaller pumping stations (3.3a)

$X_m^k \geq 2$ for the WPPs' pumping stations (3.3b)

It is desirable but not essential to meet these constraints because there is no built in cost for turning pumps *on/off*. However, keeping in mind the practical aspect, a minimum pumping time is required.

c) Flow continuity:

$$\Sigma_{m=1}^{Mn} (X_m^k Q_m^k) = F_v T_v + V^k \tag{3.4}$$

where V^k = consumer demand during control interval k (ML);

F_v = fixed valve constraint on filling/emptying the reservoir (ML/h);

T_v = effective time when fixed valve to/from reservoir is open @ F_v (hours);

Note: F_v is positive for filling and negative for emptying operation.

For the filling operation (F_v positive), water pumped (expression on the left of the equality sign) must go into the reservoir (first part on the right of the equality sign) and meet consumer demand (second part). For the emptying operation (F_v negative), water pumped plus reservoir releases must equal consumer demand. The reservoir releases are total volumes of water moving in or out of a reservoir during the control interval. The fixed valve constraint is slightly lower than the pipe constraint (pipe size and maximum target velocity of 1.5 m/s) to account for pressure loss from the entrance and exit conditions at the reservoir and pressure loss at the valve. The effective time when the fixed valve is open represents the time it would take to move water in or out of a reservoir at the maximum possible flow rate (which is the fixed valve constraint) to balance the flow continuity equation. For the duration of the control interval, the total volume of water in or out of the reservoir will be subdivided into hourly volumes. Hourly reservoir releases are governed by hourly water balances with effective flow rates between zero and the hourly fixed valve constraint.

d) Reservoir storage volumes:

$$[S^k = S^{k-1} + F_v T_v] \geq S^{min} \tag{3.5a}$$

$$[S^k = S^{k-1} + F_v T_v] \leq S^{max} \tag{3.5b}$$

where S^k = storage volume at the end of control interval k (ML);
S^{k-1} = storage volume at the start of control interval k (ML);
S^{min} = minimum storage volume (ML);
S^{max} = maximum storage volume (ML);

The minimum storage volume is determined from fire protection, emergency needs, flow balancing and/or pressure requirements and therefore has a built-in safety coefficient. Piqueiro et al. (1991) indicate that too often this value is overestimated. If a reduction of operating costs is desirable, a good first step would be to reevaluate this parameter in light of historical data and operators' knowledge.

e) Initial and final reservoir storage volumes:

$$S^{k=0} = S^{start} \tag{3.6a}$$

$$S^{k=K} = S^{end} \tag{3.6b}$$

where S^{start} = initial storage volume (ML);

S^{end} = final storage volume (ML);

From all these constraints we can see that the unknowns are the pumping times, X_m^k , the effective time that the fixed valve is open, T_v, and the reservoir storage volume at the end of the control interval, S^k, which is a target value. T_v is a parameter but not an unknown since it can be calculated from the flow continuity equation. The control intervals (k = 1 or 2) are chosen so that at the end of the *off-peak* period, the reservoir should be full and at the end of the *peak* period, the reservoir should be at minimum volume, if the operating cost is to be minimized. Therefore, only the pumping times are unknown.

All the other parameters are taken as constant over the control interval and are determined from RMOC water supply network's historical data. The global problem of minimization is solved when the pumping times (X_m^k) at each pumping station in the network meet the global constraints imposed by the water purification plants.

The **additional constraints** that bound the problem at the WPPs are:

f) Duration of pumping within control interval k when there are two pumping stations that can supply the water (i.e. WPPs):

$$\Sigma_{m=1}^{Mn1} (X_m^k) \le T^k \quad \text{for both filling/emptying operations} \tag{3.7a}$$

$\sum_{Mn1+1}^{Mn2} (X_m^k) \leq T^k$ for both filling/emptying operations (3.7b)

$\sum_{m=1}^{Mn2} (X_m^k) \geq T^k$ for the filling operation (k = 1) (3.7c)

where M_{n2} = maximum number of pump combinations for both pumping stations;

M_{n1} = maximum number of pump combinations for the first pumping station;

During the *off-peak* period, each pumping station can supply water for a duration less than the control interval (Equations 3.7a and 3.7b) as long as the total pumping time is at least as long as the control interval, to meet consumer demand (Equation 3.7c). During the *peak* period, the duration of pumping and reservoir releases is controlled by the hourly water balance.

g) WPPs' capacities

The two WPPs are designed to supply a total of 640 ML/d in the summer and 560 ML/d in the winter. As discussed before, pipe size is more of a concern than pumping capacity except for Lemieux Island WPP treatment capacity. It should be noted that the Fleet Street pumping station generates no pumping costs (only treatment and base load costs) since the turbine pumps are run from the head differential with the Ottawa River (Chapter 1).

The output from Level I Optimization is the electricity cost associated with the objective function, the pumping times for each pump combination and the effective time of reservoir releases (in or out) for each reservoir. The use of a spreadsheet permits simple row/column calculations that serve as double checks on the reservoir storage volumes, fixed valve transfers, water consumption and total water pumped. There is also verification that the constraints are met.

3.1.2 Level II Optimization - Creating a Pump Schedule

Level II Optimization uses very simple LP and row/column calculations to create a pump schedule from the hourly water balance based on the pumping times and pump combinations selected in Level I. Operators' knowledge becomes very important because this optimization should not be a 'black box'. The output is a pump policy that can serve as a guideline for the operators. The major decision maker is the *restriction* period which varies from month to month but with great season variability. For example, in July the *restriction* period is from 10:00 to 16:00 weekdays. In January, it is from 9:00 to 11:00 and from 16:30 to 19:00 weekdays. The reservoir releases should be greatest during these periods. The proposed pumping schedules are based on minimum operation cost and are not always practical. 'Fine tuning' is required to obtain more realistic schedules even if it affects costs.

Essentially, the 'model' is in fact many different models, one for each basic structure in the network (pumping station, reservoir, water demand zone) and one per control interval. Therefore, the repetitive nature of the work in terms of solving LP, but also in terms of assessing the impact of different water management alternatives, is nicely tackled by the many advanced features of spreadsheets (especially software designed for *Microsoft* Windows). The fact that it is a familiar computer environment for water managers should not be underestimated.

CHAPTER 4

NOMENCLATURE AND METHODOLOGY

4.1 DATA USED

Regarding the analytical work, pumping station data, reservoir data and consumption data are supplied for the two minor branches: Hurdman Bridge and Billings Bridge; and the two major branches: Carlington Heights and Glen Cairn/Stittsville, including Barrhaven sub-branch. Basically, there are three levels of pump information:

(i) the model outputs pumping times (X_m) for different pump combinations identified by number (e.g. X1, X5) for each branch;

(ii) the table of pump combinations for that particular branch will identify the pumps by Optimization Pump Code which is descriptive whenever possible, i.e. S for a ***small*** capacity pump compared to **B** for a ***big*** capacity pump; **E** for ***electrical*** compared to **D** for ***dual drive*** or ***diesel*** (e.g. X1 = **E**, X5 = **ED**). These codes were necessary because the pump identification used by RMOC have too many characters (e.g. PD/PE-7). It should be noted that a pump can be electrical and small or dual drive and big but only one character will be used;

(iii) the table of pumps for a particular pumping station for that branch will provide all additional information about the individual pumps, e.g. in Carlington Heights Branch, pump combinations X1 and X5 refer to the BR1W pumping station where Optimization Pump Code **E** means: ***electrical*** pump PE-3, speed = 900 rpm, capacity = 63.6 ML/d, head = 65.5 m, electricity consumption = 800 HP or 597 kW; and **D** means: ***dual drive*** pump PD/PE-7, speed = 890 rpm, capacity = 63.6 ML/d, head = 65.5 m, electrical consumption = 900 HP or 671 kW; therefore X5 = **ED**, is the combination of those two pumps in parallel.

The pipe constraint is calculated from the pipe size assuming a maximum target water velocity of 1.5 m/s (Q = vA; Q is the discharge, v is the average velocity, and A is the cross-sectional area of the pipe) which is the standard in the industry. It is used as a limiting factor for the number of possible pump combinations and should not be considered as rigid in terms of evaluating different water management alternatives. All the data was supplied by RMOC and is stored in a Quattro Pro spreadsheet to be used by the model.

4.1.1 Hurdman Bridge Branch

The Hurdman Bridge Branch in zone 1E comprises the Hurdman Bridge pumping station (code name: HB1E). The pumping station inlet/outlet pipe size is 1219 mm and the major pipe constraint is 151.3 ML/d based on a maximum target velocity of 1.5 m/s, as mentioned above, but in actual operations 185.4 ML/d is allowed. There are four pumps within the station: two ***electrical*** (**E**) and two ***dual drive*** (**D**), all with a capacity of 92.7 ML/d, a head of 13.7 m, constant speed and an electrical consumption of 373 kW. Therefore, there are 8 different electrical pump combinations possible. Only 5 remain subject to the pipe constraint, and practically, there are only 2 choices: 1 or 2 pumps *on* (see Table 4.1).

The reservoirs involved are Orléans, Montréal Road, and Innes Road (grouped under code name: R1E). The characteristics of operations of the 'effective' reservoir are listed in Table 4.2. Consumption data include zones 1E, 2E and Montréal Road (MTL) and are presented in Figure 4.1.

4.1.2 Billings Bridge Branch

The Billings Bridge Branch in zone 2C comprises the Billings Bridge pumping station (code name: BB2C). The pumping station inlet/outlet pipe size is 1067 mm and the major pipe constraint is 116.0 ML/d. There are five pumps within the station: two electrical ***small*** (S), two dual drive ***big*** (**B**), and one electrical ***big*** (**B**). The ***small*** pumps have a capacity of 19.6 ML/d and an electrical consumption of 131 kW. The ***big*** pumps have a capacity of 37.3 ML/d and an electrical consumption of 224 kW. Both ***small*** and ***big*** pumps have a head of 42.1 m and constant speed. There are 11 different electrical pump combinations possible. Subject to the pipe constraint, 9 remain (Table 4.3).

The reservoir is Ottawa South (code name: R2C). It is an elevated tank with minimum storage. The characteristics of operations are listed in Table 4.4. Consumption data presented in Figure 4.2 include zones 2C and South Gloucester (SGL).

4.1.3 Carlington Heights Branch

The Carlington Heights Branch in zone 1W comprises 3 WPPs' pumping stations: Britannia 1W, Lemieux Island 1W, and Fleet Street 1W (code names: BR1W, LI1W, and FS1W). The pumping stations' inlet/outlet pipe sizes are respectively 1219, 1372 and 1219 mm. The major pipe constraint at Britannia WPP is 160.0 ML/d. For Lemieux Island WPP, the major constraint is the treatment capacity of 290.0 ML/d. Therefore LI1W and FS1W pumping stations must be dealt with together.

There are four pumps within the BR1W station: one ***big*** diesel only (**B**), two ***electrical*** (**E**, one is ***small*** S) and one ***dual drive*** (**D**). The characteristics are listed in Table 4.5a. There are 7 different electrical pump combinations possible, all within the pipe constraint. LI1W station also has four pumps: three electrical (one ***big***, **B**; two ***electrical***, E) and one dual drive ***big***, **B** (Table 4.5b). FS1W station has five <u>turbine</u> pumps: two ***big***,

B and three ***small***, S (Table 4.5c). Since there is no cost associated with running Fleet Street pumps, the total number of electrical pump combinations from stations LI1W and FS1W together is counted with at least 3 of the turbine pumps *on*: 30 possibilities down to 13 with the treatment capacity constraint. FS1W pumps can also be used by themselves (not in combinations with LI1W pumps), but a minimum of three pumps is still desirable yielding 6 possible combinations. For all three pumping stations (effectively: BR1W, LI1W+FS1W, and FS1W), there are a total of 20 possible pump combinations (Table 4.6).

This branch's reservoir is the Carlington Heights reservoir (code name: R1W). This is the largest reservoir in the network. The characteristics of operations are listed in Table 4.7. Consumption data for zone 1W is presented in Figure 4.3.

4.1.4 Glen Cairn/Stittsville Branch (Including Barrhaven Sub-Branch)

The Glen Cairn/Stittsville Branch in zone 2W comprises one WPP's pumping station, Britannia 2W (code name: BR2W); another pumping station linking pressure zones 1W and 2W (CH2W); and the Barrhaven pumping station (BHPS). The pumping stations' inlet/outlet pipe sizes are respectively 1524, 610 and 914 mm. The major pipe constraints are 236.6 ML/d for Britannia 2W; 37.9 ML/d for CH2W; and 85.1 ML/d for Barrhaven. There are four pumps within the BR2W station: one ***diesel*** only (**D**), two ***electrical*** (**E**, one is ***small*** **S**) and one ***big*** dual drive (**B**). The characteristics are listed in Table 4.8a. There are 7 different electrical pump combinations possible, all within the pipe constraint. CH2W station also has four pumps: three electrical (two ***small*** S and one ***big*** **B**) and one ***big*** dual drive (**B**) (Table 4.8b). Although there are 8 possible pump combinations, only 3 are within the pipe constraint. Therefore, 10 pump combinations are possible for this branch (Table 4.9), the Barrhaven pumping station being run independently (refer to the Network Schematic, Figure 3.1).

Barrhaven station has five pumps: two ***dual drive*** (**D**, one is ***big*** **B**) and three

electrical (two E and one ***small*** S) (Table 4.10). There are 23 possible pump combinations with the pipe constraint at 85.1 ML/d. To take into account the real operations at Barrhaven, a 'large flow' pipe constraint of 50.0 ML/d is introduced, reducing the number of pump combinations to 13 (Table 4.11). The Barrhaven pumping station supplies water directly to the demand in zone BAR because of pressure reasons.

The reservoirs involved are Glen Cairn and Stittsville (grouped under code name: R2W) and Barrhaven (RBAR). The characteristics of operations of both reservoirs are listed in Tables 4.12a and 4.12b. Consumption data for zones 2W and BAR are presented in Figures 4.4a and 4.4b.

4.2 ELECTRICITY RATES

As mentioned in Chapter 1, Ottawa Hydro bills users according to demand and consumption. The demand load is very difficult to account for but is not expected to vary by more than plus or minus 5% with improved pump scheduling at the WPPs. The WPPs are in the 2000-5000 kW demand bracket, with higher demand load in summer compared to winter (Britannia WPP: +1.01%; Lemieux Island WPP: +9.93%) while demand rates are lower for summer than winter. Demand and consumption rates are 'stepped': they are divided into blocks with different rates (Table 4.13). For demand, the first 50 kW of the month have no charge while the next 4950 kW are billed at $5.40/kW during winter and at $4.20/kW during summer ("General Service Time-Of-Use"). There are no *off-peak* charges simply because the highest demand will occur during *peak* hours. These are based on 1993 rates (no increase in 1994), a copy of Ottawa Hydro's 1994 commercial rates is included in Appendix D. For consumption, the rates are stepped in four blocks: (i) the first 250 kW.h in the month, (ii) the next 6625 kW.h, (iii) the next 1 184 000 kW.h, and (iv) all additional kW.h (refer to Appendix D). The third step is used in the model. This is because the electricity costs are calculated by the month and the first two steps add up to 6875 kW.h, which represents only 28% of the smallest daily consumption calculated by our model at the WPPs (Lemieux Island / winter). In all cases, the first 6875 kW.h will be recorded in the first 7 hours of the first day of the month, with all days of the rest of the month in the third step mentioned above.

For pumping stations other than at WPPs, demand and consumption rates are also 'stepped' but the rates are the same for *peak* and *off-peak*, summer and winter. Consumption rates 'steps' for Ottawa Hydro "General Service" (pumping stations: HB1E, BB2C, CH2W) are divided in four blocks: (i) the first 250 kW.h in the month, (ii) the next 12 250 kW.h, (iii) the next 1 983 900 kW.h, and (iv) all additional kW.h (refer to Appendix D). Again, the <u>third step</u> is used in the model for the same reasons stated above. For Barrhaven pumping station in the City of Nepean, the third block is the next 2 129 000 kW.h and also the one used in the model.

In the compilation of energy costs presented in Chapter 5, the monthly total is adjusted to reflect the two first blocks of consumption rates. Very importantly, there is a 1/3 discount *off* the "General Time-Of-Use" rates to allow for Ottawa Hydro's 'peak shaving'. This discount is accounted for in the objective function of the WPPs' pumping stations.

4.3 *BORLAND'S* QUATTRO PRO SPREADSHEET AND THE <u>*OPTIMIZER*</u> TOOL

Borland's Quattro Pro spreadsheets are called notebooks. A notebook contains many pages, each page consisting of an array of cells in columns and rows. A cell can contain numbers, text or formulas. RMOC's water supply network data is stored in a notebook called 'NETWKOPT.WB1'. The first five pages include all data and models for each of the branches and are named accordingly: Hurdman Bridge, Billings Bridge, Carlington Heights, Glen Cairn/Stittsville, and Barrhaven. In general, the data stored in a page follows the format highlighted above: pumping station data, reservoir data and consumption data but it also includes optimization data: electricity rates in effect for that branch and a summary of possible electrical pump combinations used by the model. The objective function and constraints for that particular branch follow in text form. Finally, the optimization formulation and models for typical July and January days and for the two control intervals are stored (summer night, summer day, winter night, winter day). The two following pages include the compilation and summary of daily and monthly energy costs for typical days of summer and winter. These energy costs include the pumping, treatment and base load costs as well as the step function of the electricity rates.

4.3.1 Level I - Optimization

An example of Level I output is presented in Figure 4.5, it is the optimization output from the Glen Cairn/Stittsville branch for 'summer night' (T^k = 8 hours). The objective function is expressed mathematically as Equation 3.1 in the shaded cell reading 273.61$. Immediately under and also shaded are the variable cells, pumping times (X_m) for each of the 10 possible pump combinations followed by two additional variable cells, effective times that the fixed valves to both reservoirs (T_v) are open. Thus there are two T_v in this branch (T_{vw} for the R2W reservoir and T_{vb} for the RBAR reservoir). All the variable cells have an initial value of zero. If a particular pump combination is selected by the model, in this case pump combinations X1 and X5 are selected for respectively 3.2429 hours and 4.7571 hours, the word "Yes" appears in the right column as a visual flag. Also, to the left, the decomposition of the operating costs per pumping station is shown.

The reservoir storage volumes at the beginning (S^{k-1}) of the control interval ('night' in this case) are set at minimum for both reservoirs. The reservoir storage volumes at the end of the control interval (S^k) are calculated using the expression within brackets in Equation 3.5a. The minimum and maximum reservoir volumes for each reservoir are indicated to the right for easy comparison. The reservoir releases are referred to as fixed valve transfers (F_vT_v) to better represent the fact that water flows into the reservoir during the night (instead of 'reservoir releases'). The fixed valve transfers for each reservoir and water consumption (V^k) for each zone are calculated, then the two are summed up in the next shaded cell (second part of Equation 3.4). Water pumped at each pumping station is calculated from the first part of Equation 3.4 and the total is entered in the shaded cell. The flow continuity can then be checked since the two expressions (shaded and framed) should be the same.

The next set of shaded cells contain mathematical expressions relating to the constraints bounding the problem. The first three (*1a*, *1b and 1c*) are Equations 3.7a, 3.7b and 3.7c referring to the duration of the control interval. The next one (*2*) relates to flow continuity (first part minus second part of Equation 3.4 should give zero). The precision expected is plus or minus 10^{-4}. The next four (*3*) are Equations 3.5a and 3.5b for each reservoir. While the next two (*4*) are Equation 3.6b for each reservoir. The last shaded cell (*5*) indicates that Equations 3.3a and 3.3b were desirable but not essential. Again, the right column gives some visual indication if the conditions are met.

The linear programming formulation as used in the ***Optimizer*** tool is shown in Figure 4.6 for the same branch and control interval. The first shaded area shows the three main part of the mathematical formulation of the objective function: where the solution cell is (+D3), where the variable cells are (@COUNT(D4..D15)) and what the goal is (Minimize). The @COUNT function is not used to return the number of non-blank cells but to define a block to be used in ***Optimizer***. The next block (unshaded cells) are the variable cells bounded to be positive. The last shaded block refers to the mathematical formulation of the constraints mentioned in the preceding paragraph.

To open ***Optimizer***, choose "Tools/Optimizer" in *Borland's* Quattro Pro main menu. Since the models are already designed for each branch and control interval, choose "Options" then "Load Model". The model is loaded by pointing to the cell reading

"Solution Cell" where the model is saved in the spreadsheet (in the "H" column, same row as the objective function for each of the different models). The maximum time and maximum iterations are changed to the maximum value of 1000, the precision (accuracy of the solution) is set to 1 x 10^{-4} and the tolerance (maximum percentage a solution can differ from a theoretical optimum integer solution) to 0.05. Estimates is set to "Tangent", meaning that the initial estimates of the basic variables in each iteration are obtained from linear extrapolation from a tangent vector (as opposed to "Quadratic"). Derivatives is set to "Forward", indicating that the partial derivatives are calculated by forward differencing (as opposed to "Central"). Search is set to "Newton" for computing the search direction using a quasi-Newton method (as opposed to "Conjugate"). The ***Optimizer*** is ready to SOLVE for Level I optimization. In some cases, the maximum time is exceeded but using SOLVE again will resume the optimization. Two other messages sometimes appear: "Objective function changes too slowly" or "No feasible solution can be found"; but it does not mean that the optimization has failed. Often, it means that the desired precision can not be attained. A quick investigation of the solution given by ***Optimizer*** at this point and a good knowledge of the network will provide the answer concerning those messages.

4.3.2 Level II - Optimization

Level II optimization is performed to create a pumping schedule. An hourly water balance table is produced from hourly coefficients for pump combinations selected in Level I. The water balance is produced from a combination of simple LP that solves hourly flow continuity equations and simple spreadsheet row/column calculations. The objective function is the flow continuity equation for the duration of the control interval. These are the constraints for the night control interval (k = 1): (i) the pumping times must add to one for each hour no matter how many pumping stations are involved; (ii) the fixed valve transfers must be positive (filling the reservoir at night) for each hour. For the day control interval (k = 2), the constraints are: (i) the pumping times must be less or equal to one for each hour for each pumping station involved; (ii) the fixed valve transfers must be negative (emptying the reservoir at day) for each hour. For both night and day control intervals, the pumping times over the duration of the control interval for each pump combination must add up to the values given in Level I.

In Table 4.14, the cell containing the objective function is the one shaded in the last column. The variable cells are the hourly coefficients for both pump combinations (shaded cells in columns 2 and 3). The three constraints mentioned above are in columns 4 and 5 and in the second to last row (" Total = "). A visual indication is given that the objective is attained ("Yes" in the bottom row, last column, if the number is between plus or minus 10^{-4}, which is the desired precision). Figure 4.7 shows the ***Optimizer*** mathematical formulation of the problem. The objective function (or 'solution cell') is stored in cell "+E78", the variable cells which are the hourly coefficients are stored in "B70..C77". The goal is to "Equal" the flow continuity equation to zero. The unshaded block contains the constraints. Loading and solving this model will establish the hourly coefficients to be used in the hourly water balance or pump schedule (Table 4.15).

Producing a pump schedule is a typical application of spreadsheets. Water pumped from both pumping stations from this branch are shown in the first shaded block. They are calculated from the product of the hourly coefficients from the LP and the rated discharges of the selected pump combinations which are stored in the spreadsheet. Water consumption data are also stored in the spreadsheet and the values are linked to these cells so that any changes in the data are reflected in the pump schedule. The last column shows the fixed valve transfers from simple column calculations (water pumped in the second and third column minus water consumption in the fourth and fifth column). The bottom shaded rows are double checks between the sum of hourly flows and the total for the control interval. The model is stored from column "H" in rows adjacent to Level II - hourly coefficients table.

There are some minor variations from branch to branch depending on water consumption patterns, number of reservoirs and/or pumping stations involved and also on the kind of results obtained from the different models. Three branches can be run independently: Hurdman Bridge, Billings Bridge and Barrhaven. The results are then used in the two major branches: Carlington Heights and Glen Cairn/Stittsville, where the potential for operating costs savings are the most important since their pumping stations are large electricity users and they are subject to "General Time-Of-Use" rates from Ottawa Hydro. Spatial decomposition as well as the use of two control intervals (day and night) permit the use of a Quattro Pro spreadsheet and the ***Optimizer*** tool to create the improved pumping schedules. Water managers that are experienced spreadsheet users will understand the format of the spreadsheet easily and will be able to incorporate operators' knowledge in producing realistic pumping schedules. Also, the readily available graphics interface can be used to aid in the interpretation of results.

CHAPTER 5

RESULTS

The first section will present results of Levels I and II optimizations for the four branches and Barrhaven sub-branch for a typical day in July and a typical day in January. The second section will present the compilation of energy costs for the same typical days. Monthly estimations of those costs will be compared to Ottawa Hydro's bills for the WPPs. The comparison is used to judge if the model is 'realistic' enough to be used in further analyses. Since the models have not been calibrated and it would be very time and labor consuming to do so, the comparison **cannot** be used to assess the efficiency of the model. The third section will present the analyses performed to assess the impact of different management alternatives on the energy costs. Another important aspect investigated is the impact of increasing water demand in the network. Finally, cost-benefit relationships will be developed wherever possible. Discussion elements are included throughout this chapter although the majors points are discussed in details in the next chapter.

5.1 LEVELS I AND II OPTIMIZATIONS RESULTS

The network schematic in Figure 3.1 outlines the basic structure: pumping station, reservoir and water consumption zone used by all the different models. It should be noted that the first control interval (night) starts at 23:00 hours and ends at 07:00 hours: consumption data at 23:00 hours and 24:00 hours should be values from the day before. But '*typical* days' consumption data provided by RMOC are sets of 24 hourly values from

01:00 hours to 24:00 hours therefore, for simplicity, values provided for 23:00 hours and 24:00 hours are taken as being from the day before. Also, the reservoir storage is assumed to be at minimum volume at 23:00 hours. [An optimized pump schedule is based on water being drawn from the reservoir during the day until that minimum value is attained]. Since the electricity costs for Ottawa Hydro's "General Service" and for the City of Nepean are the same for night and day, the primary incentive for optimization in the minor branches is to lessen the burden on the major branches during the day by proper pump scheduling. All the linear programming formulations for ***Optimizer*** (e.g. Figures 4.6 and 4.7) are presented in Appendix C.

5.1.1 Hurdman Bridge Branch

As mentioned in Chapter 4, this branch has two possible pump combinations: one or two pumps *on*. The one-pump capacity (92.7 ML/d) is large compared to all the other pumps in the network (largest is 136.1 ML/d at LI1W). The power consumption factor (U_m = 96.57 kW.h/ML) for both pump combinations is the lowest in the network. Total reservoir storage volume is the second largest in the network (89.7 ML compared to 109.1 ML at Carlington Heights branch); so is the operating volume in the summer (37.8 ML compared to 40.6 ML at Carlington Heights). The operating volume in the winter is the largest in the network (48.0 ML). Water consumption in this branch amounts to approximately 27% of total water consumption in RMOC. Water consumption in the summer is 23.6% higher than in the winter.

The output from Level I for summer night is presented in Figure 5.1; and the corresponding pump schedule (Level II) in Table 5.1. No Level II optimization is necessary since the pump combinations are so simple. The model selects two pumps *on* for 7 hours 35 minutes and during the remaining 25 minutes, only one pump is *on*. Since there is no restricted time during the night, those 25 minutes can happen anytime. The pump schedule is also an hourly water balance: water is stored in the reservoirs during each hour at the flow rate indicated in the last column. The objective function minimized yields an operating cost of $326.77 for that control interval.

The results for summer day are shown in Figure 5.2; and the corresponding pump schedule in Table 5.2. Again no Level II optimization is necessary. One pump is *on* for almost 13 hours ("*" in the table indicates the fact that, at that particular time, the pump is used for only a portion of the hour), while the rest of the time water is drawn from the reservoirs. In July, the *restriction* period at the WPPs is from 10:00 hours to 16:00 hours (as indicated in Table 5.2), therefore that is when the pump is turned *off* since all water pumped at Hurdman Bridge has a corresponding energy cost in treatment and pumping from Lemieux Island WPP. The operating costs from pumping are $271.76 for a total of $598.53 for the 24-hour typical summer day. With the base load at Hurdman Bridge pumping station, the total energy cost amounts to $743.76 for a total of 110.28 ML of water pumped.

For winter, the operating volume is so large that it is not possible to fill the reservoir if it is at minimum volume at 23:00 hours, with a two-pump capacity of 7.725 ML/h (185.4 ML/d). Using the two pumps for 8 hours will provide an operating volume of 41.3846 ML (S^{min} = 48.3154 ML, indicated by "*" in the figure). Therefore, during winter, only a portion of the available operating volume is actually in use but this portion is larger than the operating volume during the summer. Figure 5.3 presents Level I output for winter night and Table 5.3 the corresponding pump schedule. The minimum cost for this control interval is $335.40.

Figure 5.4 shows Level I output for winter day and Table 5.4 the corresponding pump schedule. One pump is used for 7 hours 6 minutes while water is drawn from the reservoirs the rest of the time to the set minimum value of 48.3154 ML (indicated as "*" in the figure). In January, the *restriction* period is from 09:00 hours to 11:00 hours and from 16:30 hours to 19:00 hours as indicated on the pump schedule. The pumping costs amount to $148.87 during this control interval, for a total of $484.27 for the 24-hour typical winter day. With the base load, the total energy cost amounts to $601.77 for 89.23 ML of water pumped.

5.1.2 Billings Bridge Branch

This branch has 9 possible pump combinations. Total reservoir storage volume is the smallest in the network (3.4 ML), and the operating volumes in summer and winter are also the smallest (1.1 ML and 0.9 ML). Water consumption in this branch amounts to approximately 12% of total water consumption in RMOC. Water consumption in the summer is 43.4% higher than in the winter. Because water consumption is relatively low and constant from 23:00 hours to 6:00 hours and the reservoir volume to fill is small (does not require a lot of time), the control interval is set at 6 hours (instead of the 8-hour period) for the night and 18 hours for the day. Experience with the model for that branch proved this arrangement to be more convenient due to the lack of flexibility from the small reservoir volume.

The output from Level I for summer night is presented in Figure 5.5; and the corresponding pump schedule in Table 5.5a, while the output from Level II optimization is given in Table 5.5b. Pump combinations #1 and #2 (corresponding respectively to pumps S and **B**) are *on* for 1 hour 12 minutes and 4 hours 48 minutes. Table 5.5b gives the hourly coefficients for each pump combination from simple LP (discussed in Chapter 3 and 4). While it might not seem realistic to turn pumps *on/off* every 12 and 48 minutes, it does yield the minimum operating cost ($69.26). This is in part due to the low flexibility from such small operating volume.

The results for summer day are shown in Figure 5.6; and the corresponding pump schedule in Table 5.6a. Level II optimization is presented in Table 5.6b. Three pump combinations are selected in Level I: #2, #5 and #8 (**B**, **BB** and **BBB**, respectively; those pump combinations having the smallest power consumption factor). Table 5.6b lists the hourly coefficients for each pump combination so that the hourly water balance (Table 5.6a) respects the constraint of no flow into the reservoir during the day. The margin of error is so small, because of the small operating volume, that it is a secondary concern to optimize reservoir releases during the WPPs' *restriction* period, although all water pumped at Billings Bridge (like Hurdman Bridge) has a corresponding energy cost in treatment and pumping from Lemieux Island. The operating costs for pumping are $364.42 during the day, for a total of $433.68 for the 24-hour typical summer day. With the base load at Billings Bridge pumping station, the total energy cost amounts to $561.52 for 53.43 ML of water pumped.

Figure 5.7 shows Level I output for winter night and Table 5.7 the corresponding pump schedule. The hourly water consumption for winter night is smaller at each hour than the smallest pump discharge (0.8167 ML/h or 19.6 ML/d). Therefore, it is impossible to pump for the duration of the control interval (Equation 3.2) during the night (6 hours). There are two possibilities depending on operators' knowledge, either the constraint mentioned above is violated or water is pumped in excess. The last choice has the larger energy cost and thus, is the conservative option for evaluating operating costs for pumping ($44.17).

The results for winter day are shown in Figure 5.8; and the corresponding pump schedule in Table 5.8a. Level II optimization is presented in Table 5.8b. Two pump combinations are selected in Level I: #2 and #5 (**B** and **BB**; lowest power consumption factor). Table 5.8b lists the hourly coefficients for each of the two pump combinations. The same logic applies in creating the pump schedule with such a small margin of error. January's *restriction* period applies (indicated in the two tables, the second portion starting at 16:30 hours). The operating costs for pumping during the day are $264.24, for a total of $308.42 for the 24-hour typical winter day. With the base load, the total energy cost amounts to $394.34 for 37.52 ML of water pumped.

For the Billings Bridge branch output to be used in the Carlington Heights branch model, the 6-hour/18-hour scheme (*off-peak* and *peak* periods' duration) has to be converted to a 8-hour/16-hour scheme. This is done by adding the water consumption data for 23:00 hours and 24:00 hours to the 6-hour pumping scheme and to subtract them from the 18-hour pumping scheme.

5.1.3 Carlington Heights Branch

Carlington Heights is a major branch in the network, governing three of the WPPs' pumping stations: BR1W, LI1W and FS1W. These pumping stations supply water to the Hurdman Bridge and Billings Bridge branches as well as to the Glen Cairn/Stittsville branch through CH2W pumping station drawing water from R1W reservoir. To account for water treatment at the WPPs, the power consumption used during the treatment process is added to the cost of pumping. The overall treatment costs at Lemieux Island are higher than at Britannia water purification plant (110 kW.h/ML compared to 80 kW.h/ML). As mentioned in preceding chapters, Fleet Street (FS1W) pumping station runs turbine pumps from the head differential with the Ottawa River. Therefore, in considering the possible pump combinations, there is always a minimum of three pumps *on* at FS1W. For that reason, pumps from LI1W are used in combination with the three-pump scheme as restricted by the Lemieux Island WPP treatment capacity constraint. Power consumption factors for those pump combinations (LI1W+FS1W) take into account the pumping cost for only the LI1W pumps and Lemieux Island treatment cost for all water pumped. For BR1W, the power consumption factor for treatment at Britannia WPP is simply added to the pumping power consumption factor. For FS1W, there is only a treatment cost from Lemieux Island WPP.

Carlington Heights has the largest total reservoir volume and summer operating volume in the network (respectively, 109.1 ML and 40.6 ML). Water consumption in that branch amounts to approximately 36% of total water consumption in RMOC. Water consumption in the summer is 18.9% higher than in the winter.

The output from Level I for summer night is presented in Figure 5.9; and the corresponding pump schedule in Table 5.9 . Pump combinations #7 and #8 (corresponding respectively to the largest pump capacity for BR1W and LI1W+FS1W) are *on* for the duration of the control interval (8 hours, no need for Level II optimization). This is insufficient to fill the R1W reservoir to full capacity while filling reservoirs in the Hurdman Bridge and Billings Bridge branches at the same time as satisfying water demand in zones 1E, 2C and 1W. As such, constraint 4 in the figure is violated ("No" appears next to it in the right column). "No" also appears next to constraint 2 but this is a matter of precision due to the inability to conform to constraint 4 ('precision' is explained in Chapter 4). Under these conditions, the minimum operating cost for pumping (with treatment costs and 1/3 *off* discount included) is $519.25 and the maximum pumping capacity for an 8-hour period is 145.00 ML.

The results for summer day are presented in Figure 5.10; and the corresponding pump schedule in Table 5.10. Pump combinations #1 and #20 are selected by the model, for 9 hours 51 minutes and 16 hours, respectively (#1 has the lowest power consumption factor for BR1W pumping station and #20 has the highest discharge for FS1W pumping station). Water is drawn from the reservoir from the maximum value of 106.5041 ML obtained from the preceding control interval. Under these conditions, all constraints are met and the energy cost is $1199.05. The total pumping and treatment cost for this 24-hour typical summer day is $1718.30. Base load and step function will be considered in the compilation of energy costs in a following section.

Results for winter night are shown in Figure 5.11; and the corresponding pump schedule is in Table 5.11a. The model selects pump combinations #7 from BR1W and #8 from LI1W+FS1W as for summer night. Again, the reservoir cannot be filled to its maximum (101.9087 ML instead of 109.1 ML) due to the fact that water is drawn by the CH2W pumping station to the 2W zone. A significant amount of water is pumped since it counterbalances the fact that winter water consumption is lower for all three water demand zones (1E, 2C and 1W). The impact of operating CH2W in this fashion will be discussed in detail in the water management alternatives section. The hourly coefficients calculated by the Level II model are given in Table 5.11b. The pumping costs under these conditions amount to $755.87 for this control interval.

For winter day, results are shown in Figure 5.12 and the corresponding pump schedule in Table 5.12a. The model selects pump combination #15, #16, #18, #19 and #20, all pump combinations from the FS1W pumping station (no pumping costs). This is a good example of minimum cost optimization without realistic application. Operators' knowledge and 'fine tuning' is required to evaluate potential pump schedules that allow for a slightly higher cost but with more practical application. The hourly coefficients for the optimized pump schedule are shown in Table 5.12b. The objective function solves for $850.55 during this control interval. The total pumping and treatment cost for this 24-hour typical winter day is $1606.42.

5.1.4 Glen Cairn/Stittsville Branch

Glen Cairn/Stittsville is the other major branch in the network with one WPP pumping station: BR2W, where treatment costs are added and "General Time-Of-Use" rates are in effect. The other pumping station is CH2W, which takes already treated water from the R1W reservoir, is subject to "General Service" rates, and has a small pumping capacity. With both pumping stations, there are 10 possible pump combinations. The peculiarity of this branch is that it has two reservoirs: R2W and RBAR; and two water demand zones: C2W and CBAR. The Barrhaven sub-branch is solved independently and will be discussed in the next section. Total reservoir volume for R2W (38.7 ML) and summer and winter operating volumes (14.9 ML and 14.6 ML) are relatively small compared to Carlington Heights and Hurdman Bridge. Water consumption data in this branch (excluding the Barrhaven sub-branch) represents about 23% of total water demand in RMOC which is less than in the Hurdman Bridge branch. Winter water consumption is 27.8% lower than water demand in the summer.

Results for summer night are presented in Figure 5.13 and the corresponding pump schedule in Table 5.13a. The model selects pump combinations #1 and #5 from BR2W pumping station (pump combinations with the two lowest power consumption factors for BR2W). No water is drawn from the R1W reservoir through CH2W. Both reservoirs are filled to maximum capacity. Table 5.13b shows the hourly coefficients from Level II optimization. The energy costs (including treatment and 1/3 *off* discount) are $273.61.

For summer day, results are presented in Figure 5.14 and the pump schedule in Table 5.14a. This time, the model selects pump combinations #1 and #10 from BR2W and CH2W respectively (lowest power consumption factors for each of the pumping stations). The hourly coefficients from Level II optimization are shown in Table 5.14b, representing approximately 29 minutes of pump combination #1 and 1 hour of pump combination #10 at each hour. This might not be acceptable at the operations level and thus, some 'fine tuning' might be required to produce a more adequate pump schedule based on operators' knowledge and based on minimum use of pumps during *restriction* hours. The energy costs (including treatment for water pumped through BR2W) for this control interval are $649.14. The total energy cost for this 24-hour typical summer day is $922.75.

Results from winter night are presented in Figure 5.15 and the pump schedule in Table 5.15a. The pump combinations selected by the model are #1 and #5 from BR2W and #10 from CH2W. Again, using CH2W pumping station in this fashion is not appropriate since it prevents R1W from filling up to its maximum value and therefore prevents optimizing reservoir releases during the day when electricity is the most expensive. The hourly coefficients are shown in Table 5.15b. Pump combination #5 is only used during a portion of the last hour (54 minutes). The energy costs for this control interval amount to $353.88.

For winter day, the results are presented in Figure 5.16 and the pump schedule in Table 5.16a. The pump combinations selected by the model are the same as for summer day (#1 and #10). The hourly coefficients are shown in Table 5.16b. Some provision is made to avoid pumping during the *restriction* period. The energy costs for this control interval amount to \$410.08. The total energy cost for this 24-hour typical winter day is \$763.96.

5.1.5 Barrhaven Sub-Branch

The Barrhaven pumping station is used to convey water to the Barrhaven consumption zone from the RBAR reservoir or the main line, therefore water is pumped uniquely to satisfy demand. There are 13 pump combinations, using electricity from the City of Nepean. Total reservoir storage (19.5 ML) and operating volumes (12.7 ML for summer and winter) are relatively large considering that water consumption in that sub-branch amounts to about 2% of total water consumption for RMOC. Winter consumption is 21.1% lower than summer's. The duration of the control intervals for this branch are 6 hours for the night and 18 hours for the day for the same reasons highlighted in the Billings Bridge section.

Results for summer night are presented in Figure 5.17 and the pump schedule appears in Table 5.17. Even the smallest pump (#4 selected by the model) has a larger capacity than the nightly water consumption, therefore water has to be pumped in excess or pumps must be turned *off* for a portion of the hour (violation of the Equation 3.2, same as Billings Bridge winter night). The energy costs of \$9.97 reflect the conservative option of pumping in excess, while the pump schedule lists the portion of the hour necessary for a good hourly water balance.

Results for summer day are presented in Figure 5.18, the pump schedule in Table 5.18a and the hourly coefficients from Level II optimization in Table 5.18b. Level I model selects pump combinations #4 and #8 for 15 hours 13 minutes and 2 hours 47 minutes respectively. As shown in Table 5.18b, each pump combination is used for a portion of the hour at each hour, making the operations very complex. Some fine tuning is desirable especially during the *restriction* hours. The energy costs for pumping during the day is $70.10. The total energy cost for this 24-hour typical summer day is $80.07. With the base load and step function (discussed in Chapter 6), the total energy cost amounts to $89.07 for 8.51 ML of water pumped.

Results for winter night are presented in Figure 5.19 and the pump schedule is identified in Table 5.19. The logic is the same as for summer night, the smallest pump being too large for the nightly water consumption. The conservative energy costs for pumping are $9.97 while the portions of the hour for each hour to satisfy water consumption are indicated in the table.

Finally, results for winter day are presented in Figure 5.20, the pump schedule in Table 5.20a and the hourly coefficients from Level II optimization in Table 5.20b. Level I model selects pump combinations #4 and #8 for 16 hours 21 minutes and 1 hour 39 minutes respectively. As shown in Table 5.18b, each pump combination is used for a portion of the hour at each hour, yielding the same problem as during the summer time. The energy costs for pumping during the day is $53.75. The total energy cost for this 24-hour typical winter day is $63.73. With the base load, it amounts to $72.00 for 6.88 ML of water pumped.

5.2 COMPILATION OF DAILY ENERGY COSTS

The compilation of daily energy costs from all the branches and for both control intervals is done independently for the two typical days in July and January. Results from Level I optimization are linked to a designated page (one for summer and one for winter) in the spreadsheet where costs are summed up and comparisons made. The operating (pumping and treatment) costs, the electricity consumption (kW.h) and the total volume pumped (ML) for each pumping station in the network are summarized in different tables.

Britannia WPP pumping stations (BR1W and BR2W) are grouped and the daily base load (i.e. heating, lighting, etc.) for the WPP is added (6259.0 kW.h/d from historical data). The night and day values for the base load are calculated proportionally to the number of hours during the control interval. [This probably overestimates the nightly value and underestimates the daytime value, that is why the summary includes only daily totals]. The "Daily Total" includes the daily base load. The "Monthly Total" is the typical day multiplied by 31 days in July or January and adjusted for the step function (discussed in Chapter 4).

The same is done for the Lemieux Island WPP pumping stations: LI1W+FS1W and FS1W. The base load for LI1W (6504.0 kW.h/d) and for FS1W (1318.0 kW.h/d) are added to the operating costs to give the "Daily Total", which is multiplied by 31 days to yield the "Monthly Total" (again adjusted for electricity step function). The operating costs per megalitre are also calculated for all the pumping stations (including and excluding the base load) but one must be careful in making comparisons since the pattern of pumping (night and day) influences the value greatly.

5.2.1 Typical Summer Day In July: Most Critical Period

Table 5.21a summarizes the summer energy costs for Britannia WPP. Total water pumped at Britannia represents 38.7% of water pumped in all of RMOC. When these values from the *uncalibrated* model are compared with the bill for Britannia WPP for the same month, a reduction of 10.25% is observed. If this was a calibrated model, this value would be in accordance with the literature (between 5 and 10%).

Table 5.21b summarizes the summer energy costs for Lemieux Island WPP. Total water pumped at Lemieux Island represents 61.3% of water pumped in all of RMOC. With the treatment costs at Lemieux Island evaluated at 110 kW.h/ML (37.5% higher than the treatment costs at Britannia WPP), total monthly costs from the *uncalibrated* model are 31.32% higher than reported in the bill for Lemieux Island WPP (Appendix D). The difference is too large to be explained by calibration only, therefore it is suspected that the power consumption factor for water treatment at Lemieux Island might be too high as mentioned in Chapters 3 and 4 and perhaps the model outputs more water from LI1W+FS1W and FS1W than from BR1W pumping station than actual operations (shifting part of the costs from Britannia WPP to Lemieux Island WPP).

Table 5.21c combines the energy costs for the two WPPs: the global difference is 4.82% (*uncalibrated* optimized operations costs higher than reported in the bills) for the most critical month of the summer. The difference is small enough so that the model may be judged acceptable to compare different water management alternatives.

Tables 5.22a, 5.22b, 5.22c, and 5.22d summarize the total energy costs for all the other pumping stations in the network. The base load for each is taken from historical data in kW.h/ML but these values include pumping costs. Therefore, for each pumping station, the base load is calculated as such: the historical value multiplied by the total volume of water pumped (ML) yields the total electricity consumption (kW.h), from this value the electricity consumption for pumping calculated from the model is deducted. The 'residual' electricity consumption is attributed to the base load. This estimate is likely overestimated since the *uncalibrated* model is expected to produce improved pump schedule and thus lower electricity consumption for pumping than the 'original' operations. Unfortunately, bills for these pumping stations are not available for comparison.

Table 5.22a shows total energy costs for Hurdman Bridge pumping station (HB1E). The historical value given to estimate the base load is lower than the power consumption factor for pumping only but is too high to be base load only. Since the base load is known to be lower than the other pumping stations, the value chosen is 120 kW.h/ML (representing 25% of total electricity consumption).

Tables 5.22b and 5.22d are for Billings Bridge and Barrhaven pumping stations.

The "*" indicates the fact that for those two pumping stations, the control intervals are 6 hours for the night and 18 hours for the day. Table 5.22c is for Carlington Heights 2W pumping station.

Of all these pumping stations, Hurdman Bridge has the lowest total energy cost per megalitre ($5.43/ML) while the other three are similar ($8.12/ML for Billings Bridge, $7.65/ML for Carlington Heights 2W, and $9.41/ML for Barrhaven pumping station). This can be attributed to the fact that more water is pumped during the night at Hurdman Bridge, therefore utilizing electricity when it is the cheapest.

5.2.2 Typical Winter Day In January

The typical day in January represents a typical day for the winter period. Ottawa Hydro's "General Time-Of-Use" rates are higher in the winter but the water consumption is much lower. Tables 5.23a and 5.23b compile operating costs and total energy costs for Britannia and Lemieux Island respectively. The "Daily Total" for Britannia during the winter is about 30% lower than summer. The monthly energy costs at Britannia WPP from the *uncalibrated* model are 33.74% lower than the bill for that winter month (Appendix D). The "Daily Total" for Lemieux Island WPP is 10.5% higher than summer. The monthly energy costs at Lemieux Island WPP from the *uncalibrated* model are 56.41% higher than the bill for that winter month. Therefore, we observe the same trend of reported costs from the model being lower for Britannia WPP and higher for Lemieux Island WPP as for the summer period. During January, Britannia WPP pumped 30.4% (38.7% for July) of the total for RMOC and Lemieux Island WPP pumped the other 69.6% (61.3% for July).

Table 5.23c combines the energy costs for the two WPPs: the global difference is 1.42% (*uncalibrated* optimized operations costs lower than reported in the bills) for that winter month. Again, the difference is small enough so that the model may be judged as acceptable to compare different water management alternatives.

Tables 5.24a, 5.24b, 5.24c, and 5.24d summarize the total energy costs for all the other pumping stations in the network for winter. All the "Daily Totals" went down except for Carlington Heights 2W pumping station which was used during the winter night (not during summer night). Total energy cost per megalitre remained the same for Hurdman Bridge and Carlington Heights during summer and winter, went up for Billings Bridge reflecting a lower percentage of nightly pumping, and went down for Barrhaven reflecting a higher percentage of nightly pumping. Electricity rates for winter are the same as summer for those pumping stations.

5.2.3 Analysis Of Total Energy Costs At The WPPs: Summer <u>And</u> Winter

As mentioned above, it is suspected that the power consumption factor for treatment at Lemieux Island WPP is too high (personal communications with André Proulx, RMOC's Director, Water Division). Assuming that the model outputs improved pump schedules (according to the literature savings between 5% and 10% can be expected from a calibrated model: Crawley and Dandy, 1993; Ormsbee et al., 1989; Tarquin and Dowdy, 1989; and Anonymous, 1988b) and taking into account the fact that calibration would lower the possible savings, the result of -4.82% presented in Table 5.21c for summer is roughly 10% lower than first expected and the result of 1.42% in Table 5.23c for winter, about 5% lower [with a power factor of 110 kW.h/ML, compared to 80 kW.h/ML for Britannia WPP]. Therefore, it is desirable to analyze the effect of a lower power factor for treatment on the compilation of energy costs for both summer and winter.

Results with a power factor value of 80 kW.h/ML (same as Britannia WPP) are presented in Tables 5.25a,b,c for summer and Tables 5.26a,b,c for winter. Savings of 4.50% for the summer from an <u>*uncalibrated*</u> model are more realistic as well as savings of

12.38% for the winter. With a power factor slightly lower than for Britannia WPP (75 kW.h/ML), savings of 6.05% for summer and 14.21% for winter *before calibration* are reached (Tables 5.27a,b,c for summer and Tables 5.28a,b,c for winter). These are the kind of values first expected out of the model. A better estimation of Lemieux Island WPP power factor for treatment is recommended. The initial value of 110 kW.h/ML is used for all the analyses but the energy costs are compared amongst model results only, therefore the impact of an overestimation is minimized.

5.3 ANALYSIS OF DIFFERENT WATER MANAGEMENT ALTERNATIVES

By careful inspection of the results, some water management alternatives can be identified and an analysis can be performed to assess their impact on the energy cost, mostly during the critical summer period. The following list identifies potential problem areas or areas of improvement that will be further studied:

- the 'real' cost involved with the use of CH2W pumping station to draw water from the R1W reservoir to the 2W zone in Glen Cairn/Stittsville branch;
- the impact of a greater operating volume in the Glen Cairn/Stittsville branch (this is already under consideration at RMOC) and developing cost-benefit relationships for that alternative;
- the impact of increasing the water demand in the Glen Cairn/Stittsville branch;
- the impact of increasing the pipe constraint in the Carlington Heights branch to allow for a larger flow capacity since the R1W reservoir could not be filled at night (increasing pipe constraint is the numerical way to represent an increase in treatment capacity at Lemieux Island WPP);
- with this increasing pipe constraint, the impact of slightly increasing the operating volume of reservoir R1E in the Hurdman Bridge branch;

- with this increasing pipe constraint, the impact of significantly increasing the operating volume of reservoir R2C in the Billings Bridge branch; and
- the impact of increasing the water demand in all branches related to Carlington Heights branch yielding the need for an increase in pipe constraint.

5.3.1 Analysis of Glen Cairn/Stittsville Branch

The Glen Cairn/Stittsville branch will be analyzed first since it has an impact on the Carlington Heights branch from the use of CH2W pumping station to draw water from the R1W reservoir to the 2W zone. It should be noted that the Barrhaven sub-branch is not further analyzed since the Barrhaven pumping station supplies the water demand for pressure reasons. No water management alternatives could be identified to improve the operations in that part of the network.

a) Impact Of CH2W Pumping Station During Summer And Winter

The model selects pump combinations from the CH2W pumping station of the Glen Cairn/Stittsville branch for these control intervals: summer day, winter night and winter day. There is a hidden cost in using this pumping station since the water has to be treated and pumped from the Lemieux Island WPP before being stored in reservoir R1W. That hidden cost will vary depending on the pump combinations selected by the model in the Carlington Heights branch. An analysis was conducted to assess the 'real' cost of pumping through CH2W.

Figures 5.21 and 5.22 present the daily energy costs obtained for summer and winter operations respectively with and without CH2W *online*. The costs shown are the total cost of treatment plus pumping plus base load at Britannia WPP, Lemieux Island WPP and Carlington Heights 2W pumping station (no treatment cost in the latter). In

Figure 5.21, the overall saving realized by <u>not</u> using CH2W is $188.85 for a typical summer day. In Figure 5.22 for a typical winter day, the saving is $51.92 from <u>not</u> using CH2W. Because CH2W pump combinations were selected during the winter night, water was drawn from R1W reservoir while it was being filled. Therefore, there is an added benefit to turn *off* the CH2W station: R1W reservoir can be filled to its maximum storage capacity during the winter period. Also, CH2W pumping station was not designed to be used on a daily basis but for emergency and pressure reasons only. For all these reasons, all following analyses will be performed with CH2W *offline*.

Figures 5.23 to 5.25 present the results from Level I Optimization for the Glen Cairn/Stittsville branch with CH2W *offline* for summer day, winter night and day (summer night model output did not select pump combinations from CH2W). Figures 5.26 to 5.28 present the results from Level I Optimization for the Carlington Heights branch with CH2W *offline* for the same control intervals. Tables 5.29a,b,c show the compilation of daily energy costs at the WPPs with CH2W *offline* for the summer period. The energy costs at Lemieux Island WPP are the same while energy costs at Britannia are higher since all the water to zone 2W is pumped through BR2W. The overall difference with the WPPs' bills is 6.39% (instead of 4.82% higher than the bills during summer with CH2W *online*) but RMOC has to pay the electricity bill for CH2W pumping station on top of that of the WPPs, yielding a higher overall cost as mentioned above. Tables 5.30a,b,c show the compilation of daily energy costs at the WPPs with CH2W *offline* for the winter period. In this case, the energy costs at Lemieux Island WPP are lower while energy costs at Britannia are higher than when CH2W is *online* for the same reason as above. The overall difference with the WPPs' bills is 9.66% higher (instead of 1.42% lower than the bills during winter with CH2W *online*) but no electricity cost for CH2W has to be added.

b) <u>Impact Of A Greater Operating Volume For R2W Reservoir</u>

By inspecting the possible pump combinations (Table 4.9), the largest flow capacity for BR2W is 9.6667 ML/h (232.0 ML/d). Therefore, the potential volume of water to be pumped during the night (8 hours) from BR2W is 77.3333 ML of which 21.6267 ML is for water consumption and 12.7000 ML for filling the RBAR reservoir. Of the remaining 43.0066 ML, 14.9000 ML are used for filling the R2W reservoir, which leaves 28.1066 ML that could potentially be stored if the R2W summer operating volume was larger. This amount is divided into 20% increases for the analysis. Note that the largest pump from CH2W pumping station could be added, but it was excluded for those reasons explained above.

Figure 5.29 illustrates the relationship between daily energy costs and increase in operating volume of the R2W reservoir for typical days in summer and winter. In terms of energy costs (pumping, treatment and base load included), the larger the operating volume the smaller the energy costs. The slope of both functions is quasi-constant suggesting that for every 20% increase in operating volume, average savings of $55.66 per summer day and of $65.55 per winter day can be expected. A rough extrapolation over 6-month summer and winter periods (183 days and 182 days, respectively) would represent savings of $22 115.88 ($10 185.78 + $11 930.10) per year per 20% increase in operating volume.

Figure 5.30 illustrates the daily energy costs per ML of operating volume in the R2W reservoir versus the increase in operating volume. The functions for summer and winter fall rapidly in the first 20% increase in operating volume and then tend to stabilize at roughly $20 per ML of operating volume. Thus, the benefits of increasing the operating volume of a reservoir are translated rapidly into savings per ML of operating volume but those benefits tend to level off.

c) <u>Cost-Benefit Relationships Of Greater Operating Volume For R2W</u>

There is a cost associated with increasing the operating volume of a reservoir. Therefore the first step is to reevaluate the safety coefficient on the minimum storage volume. Investigation of safety concerns, emergency needs, adequate fire protection, flow balancing and pressure requirements from historical data is important because decreasing even slightly the minimum storage volume, S^{min}, will increase the operating volume and thus permit savings as mentioned above. The R2W reservoir minimum storage (23.8 ML) is presently at 61.5% of the maximum value (38.7 ML) in the summer. The desirable minimum storage volume is about 35% of the maximum value, in this case it would be 13.5450 ML, translating into an increase in operating volume of 10.2550 ML (almost doubling the actual operating volume of 14.9 ML) without any construction costs. Apparently, there is a suction problem at the reservoir that prevents RMOC from operating the reservoir with a greater operating volume (personal communications with André Proulx, RMOC's Director, Water Division).

Another means of increasing the operating volume is to build additional storage facilities (in the model, increasing the maximum storage volume, S^{max}) but there are large construction costs involved. These costs are evaluated at $23 per (ML of operating volume) per day over 50 years (roughly a total cost of $420 000 per ML of operating volume), for a minimum increase of 15 ML of operating volume since no construction project would be implemented for a smaller volume (personal communications with André Proulx and John Krug, formerly RMOC's Master Plan Water Project Engineer).

Figures 5.31 illustrates the impact of increasing the operating volume of reservoir R2W on the total daily costs for summer. Actual conditions are set at zero to better show the savings from a decrease in energy costs with an increase in operating volume. As mentioned above, theoretically the operating volume can be increased by 10.2550 ML without any construction costs, yielding savings related to the decreasing slope of the energy cost function. An increase in operating volume of 15 ML and higher would necessitate construction of storage facilities. As shown in the figure, there is no optimum operating volume and therefore, an increase in operating volume cannot be justified only by savings in energy costs. In some cases, the decrease in energy costs is more pronounced and an optimum operating volume can be found. This is illustrated in an hypothetical case where the energy cost function is assumed to be nonlinear (e.g. quadratic) in Figure 5.32 (adapted from Sabet and Helweg, 1989). Clearly this is not the case for this reservoir. Thus, the decrease in energy costs serves to dampen the costs of construction and other reasons must be stated to justify the cost (e.g. increasing water demand, safety concerns, emergency needs, adequate fire protection, flow balancing and/or pressure requirements).

d) Impact Of Increasing The Water Demand

Figure 5.33 illustrates the impact of increasing water demand (V^k , in the model) on the daily energy costs. These costs will increase steadily with increasing demand but the energy costs are lower when operating from a larger operating volume. The operating volume of 14.9 ML represents actual operations and the operating value of 37.3853 ML represents a 80% increase in operating volume. With this increase in operating volume (shown as an increase in maximum reservoir storage volume, S^{max}, in the model), the daily energy costs can be kept under the present daily energy costs with an increase in water demand of up to 17.5%. Figure 5.34 shows the impact of increasing water demand with a range of increase in operating volume of reservoir R2W. Since the function is linear, only two points of data are used to draw each of the functions (which are all parallel). Looking at present conditions and maximum changes in both water demand and operating volume (0.0% increase in water demand at 0 ML of increase in operating volume and 25.0% at 22.4853 ML), we can see the dampening effect of a larger operating volume on the daily energy costs, especially with increasing water demand.

Efficient optimization of daily energy costs is only possible if the reservoir can be filled to its maximum value during the night. With an increase in water demand, there is less water available to fill a reservoir. Tables 5.31 and 5.32 show simple water balances for the Carlington Heights branch with CH2W pumping station *offline* and *online* respectively. The last column indicates the maximum possible reservoir releases (possible operating volume for R2W reservoir) considering the increase in water demand. This highlights the fact that lower energy costs should not be the only concern when evaluating the impact of increasing the operating volume.

5.3.2 Analysis of Carlington Heights Branch

The main analysis performed on the Carlington Heights branch is to allow for a larger flow capacity since the R1W reservoir could not be filled at night during the summer period. The limiting factor in this branch is the treatment capacity at the Lemieux Island WPP (290.0 ML/d in the summer). In the model, increasing the pipe constraint is the numerical way to represent an increase in treatment capacity at Lemieux Island WPP. Increasing the treatment capacity will allow for a larger flow to the distribution system. A quick investigation reveals that there is no additional constraint due to pipe size (maximum target water velocity always below 1.5 m/s) in the range of increase in pipe constraint used in the analysis (Table 5.33). The costs of increasing the treatment capacity are very difficult to estimate, therefore no cost-benefit relationships will be developed for this branch.

a) <u>Impact Of Increasing The Pipe Constraint</u>

By careful inspection of all the possible pump combinations for this branch (Table 4.6), we notice that, with the pipe constraint as it is for BR1W, all BR1W pump combinations are already selected. Therefore there is no potential flow capacity gain from this pumping station. The same holds for FS1W pumping station. But for LI1W+FS1W, keeping the FS1W three-pump scheme, there are still many pump combinations that exceed the current pipe constraint. Table 5.34 lists all the electrical pump combinations for LI1W+FS1W, the last column indicating if they met the current pipe constraint (290.0 ML/d). An analysis is done to assess the impact of increasing the pipe constraint by 2.5%, 5%, 7.5%, 10%, 12.5% and 15%. Table 5.35 lists all potential pump combinations for this branch up to an increase of 25%. The last partial column indicates the pipe constraint increase corresponding to the addition of that particular pump combination.

For example, a 2.5% increase would represent a pipe constraint of 297.25 ML/d. With this new value, additional pump combinations can be selected. In this case, #21 from Table 5.35 would be added to the model and a new optimized solution can be found. The results for all the different increases are presented in Figure 5.35. The initial decrease in the operating (treatment and pumping) costs from the initial conditions to a 2.5% increase, is small due to the fact that the R1W reservoir can now be filled to its maximum value of 109.1 ML. Under present operating conditions, decreases in daily energy costs are only possible with increases in pipe constraint of 2.5%, 5.0% and 15.0% since the new pump combinations introduced at these steps have lower power consumption factors than preceding ones. Table 5.36 ranks the new pump combinations from the lowest [discharge x power consumption factor for pumping plus treatment] to the largest. For for pump combination selection of the LI1W+FS1W pumps, discharge is an important parameter along with the power consumption factor, because power consumption factors for pumping comes from the LI1W pumps but for treatment, total discharge (LI1W+FS1W) has to be considered. Therefore, the three most efficient new pump combinations are introduced with increases in pipe constraint of 5.0%, 15.0% and 2.5% (as mentioned above).

b) <u>Impact Of Slightly Increasing The Operating Volume Of Reservoir R1E In The Hurdman Bridge Branch</u>

As mentioned previously, the model selects 2 pumps *on* for 7 hours 35 minutes for summer night in this branch. Optimization would be improved if the operating volume was increased so that the pumps could be *on* for the duration of the control interval (8 hours). This would require an additional 1.5904 ML of storage, by lowering the minimum reservoir storage volume from 51.9 ML (57.9% of maximum reservoir storage) to 50.3096 ML (56.1% of S^{max}). Figure 5.36 illustrates the impact of slightly increasing reservoir R1E operating volume in the Hurdman Bridge branch on the daily energy costs at the WPPs' pumping stations with increases in pipe constraint at the Lemieux Island WPP of 0.0%, 2.5%, 5.0% and 15.0%. Present conditions are also presented for comparison. Since the Carlington Heights R1W reservoir cannot be filled with present conditions, increasing nightly pumping in the Hurdman Bridge branch will reduce the maximum reservoir storage volume (from 106.5041 ML to 104.9137 ML). Therefore, a marginal increase in pipe constraint of 2.5% is required for full optimization of the Carlington Heights branch. The daily energy costs are only for the major branch since the daily energy costs in the minor branch are constant (more water pumped at night, less by the same amount during the day, same electricity rates for night and day for the smaller pumping stations).

c) Impact Of Significantly Increasing The Operating Volume Of Reservoir R2C In The Billings Bridge Branch

Table 5.37 presents a simple water balance based on the pumping capacity in the Carlington Heights branch and the previous increase at Hurdman Bridge, to determine how much water is available to fill a potentially larger reservoir in the Billings Bridge branch with increases in treatment capacity at Lemieux Island WPP. The 8-hour control interval has to be converted to a 6-hour interval to conform to water consumption patterns (explained in Chapter 4) in this branch. This is done by subtracting the water consumption values for 23:00 hours and 24:00 hours. The last column in the table lists the maximum possible amount of water available to fill a reservoir for 6 hours. Using increases in pipe constraint of 0.0%, 2.5%, 5.0% and 15.0% in the Carlington Heights branch, and the maximum operating volume from the table, the daily energy costs of the major branch (minor branch costs are constant, explained in preceding paragraph) are plotted on Figure 5.37. The increase in pipe constraint allows for a larger flow to the distribution system and therefore permits the optimization of the Billings Bridge branch from a larger operating volume, resulting in lower daily energy costs for the WPPs' pumping stations. The steeper slope between 2.5% to 5.0% increase in pipe constraint provides the largest savings in daily energy costs, but there are construction costs involved with increasing the treatment capacity at Lemieux Island . Figure 5.38 presents the same data but highlights the impact of the increased operating volume (in the boxes are the needed increases in pipe constraint at the Lemieux Island WPP). Considering that there are large construction costs associated with increasing the operating volume, especially in this branch where all additional ML of operating volume implies construction, there is no clear economic benefit in doing so (this will be discussed further in the next chapter).

d) Impact Of Increasing The Water Demand

Tables 5.38a and 5.38b show the opportunities for optimization (reservoir full at night) for the Hurdman Bridge and Billings Bridge branches with increases in water demand. The shaded rows are the ones where the calculated reservoir releases (last row) are larger than the given operating volume (from RMOC data). As mentioned in the Glen Cairn/Stittsville section on increasing water demand, as the amount of water required for water consumption increases, there is less water available to fill a reservoir, limiting the advantage of increasing the operating volume. For Hurdman Bridge branch, the potential for full optimization stops after 5.0% increase in demand with the original operating volume and the advantage of slightly increasing the operating volume is nil with increasing demand. For Billings Bridge branch, the operating volume is so small that optimization with the original operating volume is always achieved though not very efficiently. Actually, an operating volume of 17.4402 ML would still provide full optimization with a water demand increase of 50.0%, since water consumption is so low in this branch.

Figure 5.39 illustrates the impact of increasing water demand with an increase in pipe constraint (treatment capacity) in the Carlington Heights branch for a typical summer day. This time the slopes of the functions, for 0.0% and 15.0% increase in pipe constraint, are not parallel. The daily energy costs at the Lemieux Island WPP are lower with a 15.0% higher treatment capacity (although construction costs are needed to provide a larger treatment capacity). The difference between the original conditions (0.0% increase in pipe constraint) and the higher treatment capacity is intensified as water demand increases because, even at 0.0% water demand increase, full optimization cannot be performed (reservoir cannot be filled at night). Therefore, with higher water demand, less optimized solutions are obtained (higher energy costs).

Table 5.39 presents a simple water balance for a 25.0% increase in pipe constraint and various increases in water demand. The shaded rows highlight the potential for optimization with such a large increase in flow capacity. Water demand could be increased by as much as 50.0% under such conditions. Again the last column indicated the maximum reservoir releases compared to the actual 40.6 ML.

While no cost-benefit relationships are developed, because a thorough audit of the Lemieux Island water purification plant is beyond the scope of this project, it is clear that the slope of the daily energy costs function is not steep enough to provide a real advantage in terms of covering construction costs in the long run. As for the Glen Cairn/Stittsville branch, the decrease in daily energy costs can serve to dampen the construction costs, but other reasons must be stated to justify the cost (e.g. increasing water demand, safety concerns, emergency needs, adequate fire protection, flow balancing and/or pressure requirements).

CHAPTER 6

DISCUSSION

The results clearly show that linear programming is a good programming option to solve pump scheduling and reservoir releases problems. Also, the choice of ***Optimizer*** as a solver of linear programming problems has the considerable advantage of being available to any spreadsheet user. The most common spreadsheet software (Lotus 1-2-3, Excel, Quattro Pro) have built-in LP solvers in their advanced mathematical features. Quattro Pro's ***Optimizer*** has user-friendly menus and options that minimize possible computer programming mistakes. Thus the challenge resides in proper mathematical formulation of the problem, not in computer programming (as is often the case when designing programming code in FORTRAN, C+, Pascal, etc.; these programming languages also require compilers and basic programming knowledge which limits the number of users).

6.1 COMMENTS ON THE DATA USED

Pumping station data used in the model (or more correctly, in all the different models) are taken from RMOC records. From conversations with the RMOC Operations' Manager, pumps are assumed to discharge the rated capacity at the rated power consumption, but it should be noted that this has been challenged by many researchers (Jack et al., 1991; Tarquin and Dowdy, 1989). A potentially large error can be introduced at this stage from this assumption, but from RMOC's operators' knowledge, it is not the case here. However, actual pump curves should be developed and efficiency measured and compared with conditions assumed in this model. Even if it is labor and time consuming, it is essential to define 'real' operating conditions of pumps in the network, incorporate them in this model and analyze the results before real-time models can be developed. This holds true for both individual pumps and pump combinations. As mentioned in Chapter 4, pipe constraints are calculated from pipe sizes with an assumed average velocity of 1.5 m/s, the standard in municipal water distribution systems. The velocities could be measured for greater accuracy but with only little impact on the solution. Allowing for greater velocities would result in pressure problems and possibly backwater problems, therefore invalidating the assumption that pumps in parallel produce a discharge which is the sum of individual pump discharges.

Reservoir data are also taken from RMOC records. Fill/Empty pipe capacity is calculated from pipe size. A slightly lower value than pipe capacity is assumed for the fixed valve constraint to avoid overestimation of reservoir releases, because they are a major component in the reduction of operating costs. In RMOC, only two reservoirs have operating volumes much larger than 40.0% of their maximum reservoir storage capacity: the Barrhaven reservoir (RBAR) and the Innes Road elevated tank. The safety coefficients (the remaining 60.0% stored in the reservoir) are large and might be overestimated. Therefore, in light of historical data on emergency needs and flow balancing, it might be appropriate to reevaluate these coefficients if optimization is to be prioritized.

Consumption data are actual values for January and July 1993 in RMOC's database. The minor consumption zones are grouped with the major ones to respect the network schematic (presented in Figure 3.1). The spreadsheet format is very useful in this case since any water consumption data (e.g. *typical* day, *maximum* day, etc.) can be entered. This study uses *typical* days in summer and winter because it is concerned with day-to-day operations, not operations at *maximum* day for design of hydraulic systems. For best estimations of year round operations, *typical* days from every month can be used. The use of historical data becomes limiting whenever present day optimization is desired, depending on the time it takes to compile water demand data for each zone. Robust demand forecasting modules (e.g. based on time series analysis) are essential for real-time modelling.

Power consumption data introduces the largest error in the optimization especially coupled with the rated discharge assumption. There are many power consumption factors: for pumping, for treatment and for base load. The pumping power factor comes from the rated power consumption of the motors running the individual pumps, again 'real' curves have to be developed to minimize the error. Treatment and base load (heating, lighting, etc.) power factors are taken from the WPP's power consumption data. Detailed values from 1986 were compared to less detailed values compiled up to 1990. Trends were identified and values adjusted for 1992. Also, the base load power consumption (in kW.h/day) is taken as the residual from total power consumed at the WPP minus pumping and treatment power consumption (expressed in kW.h/ML). When the model is used for comparison between model results the error introduced is minimized, but if calibration is desirable, a complete analysis and update of power consumption data is required. Also, a method for estimating the base load at the WPPs with greater accuracy needs to be determined because it has a great impact on the compilation of energy costs, which can measure the efficiency of a calibrated model when compared to WPPs' bills.

Simplification of the water distribution system into a network schematic ('spatial decomposition') is essential for the spreadsheet approach to be efficient. The same holds true for 'time-axis' decomposition. Sophisticated models need extensive calibration and testing and are necessary if real-time telecontrol is to be achieved. The literature review shows clearly that it is not the case for pump scheduling and reservoir releases optimization. Also, the use of two simple control intervals for Level I optimization (solving for pumping times) and allowing for 'fine tuning' in light of operators' knowledge during restriction periods for Level II optimization (creating a pump schedule), is a key element in the simplification of the problem. Some researchers (Chase and Ormsbee, 1988) have used control intervals corresponding to *peak*, *off-peak* and *restriction* periods throughout the day. This approach demands that an optimum 'tank trajectory' be predetermined if a solution is to be found with limited computer facilities and time. The 'tank trajectory' determines the volume of water in the tank at different times of the 24-hour optimization period: thus, trial and error analyses have to be performed to find these optimal reservoir releases for each tank in the system.

6.2 MINOR BRANCHES AND SUB-BRANCH

The results from Level I and II optimizations for the minor branches highlight the fact that water distribution systems are designed for *maximum* day water consumption which does not always allow for efficient optimization of day-to-day operations, especially in the winter time (well below maximum design). Although the *maximum* day water distribution system design is essential to assure safety of supply to the consumers, greater flexibility in pump operations is desirable for day-to-day operations. For the minor branches (smaller pumping stations), there are no advantages in the electricity tariff structure: the rates are the same for night and day and for summer and winter. But all water pumped to those minor branches has to be first treated and then pumped from the major pumping stations at the WPPs. Therefore, there is an impact on the major branches' electricity consumption.

Also, as seen from the analyses in the Carlington Heights branch, increasing the operating volume of the different reservoirs in the system is not always the best way to optimize the daily energy costs, especially in light of increasing demand. As a reminder, efficient optimization is achieved when reservoirs can be filled to maximum capacity at night and drawn to the minimum during the day. The largest operating volume that permits this kind of operation is the optimum one in terms of daily energy costs. In RMOC's distribution system, if construction costs are involved, the savings in energy costs are not significant enough to justify the spending. Better water demand forecasting and the development of actual pump efficiency curves (discharge and power consumption) are strongly recommended for more efficient optimization. Each branch of the system has its own characteristics that have to be taken into account when developing long-term water management plans.

6.2.1 Hurdman Bridge Branch

Results from Level I optimization for typical summer and winter days show that the summer operating volume is a good size for optimization since the largest possible flow is pumped for almost the entire duration of the control interval to fill the R1E reservoir; while the winter operating volume is too large to be filled from the maximum two-pump discharge. As mentioned before, this 'effective' reservoir groups three reservoir facilities: one reservoir (Orléans), one storage tank (Montréal Road) and one elevated tank (Innes Road). Although it is called a 'minor' branch, the water consumption is roughly 27% of the total for RMOC, while the 'major' Glen Cairn/Stittsville branch water demand is about 23%. In the compilation of energy costs, the base load for the Hurdman Bridge branch has to be assumed as the residual of [120 kW.h/ML minus pumping] since the historical value of 65 kW.h/ML from RMOC records does not even cover pumping needs (96.57 kW.h/ML) and is too large to be base load only.

The potential for optimized day-to-day operations is high under present conditions and with an increase in treatment capacity at the Lemieux Island WPP, but the advantage disappears slowly with increasing water demand (full optimization up to 5.0% increase in water demand). With an approximate 15% increase in water demand, there is a loss of roughly 5% in operating volume. The limitation is the pipe size constraint which is already surpassed in actual operations (a 1219-mm pipe with a maximum target water velocity of 1.5 m/s permits a discharge of 151.3 ML/d; the actual operation permits up to 185.4 ML/d). All four pumps in the Hurdman Bridge pumping station have a flow capacity of 92.7 ML/d, therefore there is no flexibility to augment the two-pump capacity by an amount smaller than another 92.7 ML/d. The pipe size might become a serious limitation in the future and if so, the pipe should be replaced and smaller capacity pumps added for greater flexibility in day-to-day operations in light of increasing demand.

6.2.2 Billings Bridge Branch

The Billings Bridge branch is characterized by a small reservoir volume from one elevated tank (Ottawa South or 'Alta Vista'). The operating volume is 1.1 ML in the summer and 0.9 ML in the winter. The water consumption is not negligible: 12% of the total for RMOC. The water consumption pattern and the fact that it does not take a lot of time to fill the reservoir lead to better performances from models developed with different duration of control intervals: 6-hour nights and 18-hour days instead of 8-hour/16-hour intervals.

Results from Levels I and II optimizations for typical summer and winter days show that the operating volume is insufficient to truly optimize the daily energy costs: daytime pumping is very large compared to nighttime pumping. The large pipe size permits flows up to 116.0 ML/d which comprises almost all possible pump combinations. At first there seems to be a good range of pump capacities (from 19.6 ML/d to 113.8 ML/d) but in comparison to pumping needs from such small operating volume, there is no real flexibility in the low range. This is particularly apparent during the winter night control interval where the smallest pump provides too large a flow if used for the duration of the control interval. Also, the lack of flexibility in operations from the small operating volume yields pumping schedules that are unrealistic, i.e. summer day and winter day control intervals both use three pumps at each hour! This highlights the flow balancing effect of the reservoir operating volume: the flow continuity equation is much easier to satisfy when the operating volume is sufficiently large. In the compilation of energy costs, it is clear that the Billings Bridge pumping station is not as efficient as the Hurdman Bridge pumping station, yielding a daily energy cost per unit water volume pumped of \$8.12/ML compared to \$5.43/ML before base load and \$10.51/ML compared to \$6.74/ML with the base load.

Increases in treatment capacity at the Lemieux Island WPP will allow for larger flows to the distribution system and therefore permit additional potential storage volume in the Billings Bridge branch. A simple water balance is needed to determine the maximum operating volume depending on the different increases in pipe constraint. For example, an increase of 5.0% in pipe constraint would allow for an operating volume of 5.9801 ML (filled during the 6-hour night control interval). This size of operating volume in the Billings Bridge branch would permit savings in daily energy costs at the WPPs' pumping stations of $70.79 during a summer day (extrapolating for the entire summer period of 183 days: $12 954.57; and assuming a conservative 60% of this value during the winter yields savings of: $20 727.31 per year). Assuming 'daily' construction costs of $23 per ML of operating volume over 50 years[1] will yield $50 202.94 per year. Therefore, it is clear that the savings in daily energy costs at the WPPs' pumping stations are not large enough to justify the construction costs.

There are clearly other advantages (if not economic) to increase the operating volume in the Billings Bridge branch. As discussed above, day-to-day operations would be greatly facilitated with a larger operating volume, especially with increasing water demand. Pump scheduling and reservoir releases optimization opportunities are close to nil under present conditions. As water demand increases, the present range of pump capacities will be more appropriate but without any increase in reservoir storage volume, day-to-day operations will continue to be complex.

6.2.3 Barrhaven Sub-Branch

The Barrhaven sub-branch is characterized by a pumping station supplying directly the water demand without any flow balancing from a reservoir. Day-to-day operations are complex. Water consumption is only 2% of the total for RMOC and water demand patterns lead to better performances from models developed with different durations of

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[1] as suggested by André Proulx, RMOC's Director, Water Division

control interval: 6-hour nights and 18-hour days as for the Billings Bridge branch. Again there is a good range of pump capacities (from 4.5 ML/d to 84.7 ML/d under the pipe size constraint of 85.1 ML/d). That pipe constraint yields too many pump combinations with large flow capacities compared to water demand. Therefore a 'large flow' constraint is introduced at 50.0 ML/d.

Results from Levels I and II optimizations for typical summer and winter days show that, like for the Billings Bridge branch, the smallest pump provides too large a flow if used for the duration of the control interval during the winter night and the same holds true for summer night. Also, the lack of flexibility in operations due to the absence of a reservoir yields complex pumping schedules i.e. summer day and winter day control intervals both use two pumps at each hour. Under present conditions, there is no real flexibility in the low range. With increasing water demand, this will become less of a concern.

6.3 MAJOR BRANCHES

As for the minor branches, it is clear that RMOC's water distribution system was designed for *maximum* day water consumption to assure safety of supply to consumers. For efficient optimization of day-to-day operations (especially in the winter time when water consumption is well below maximum design), greater flexibility in pump operations is desirable. Ottawa Hydro's electricity billing structure offers great opportunities for pump scheduling and reservoir releases optimization. The discount offered as an incentive for Ottawa Hydro's 'peak shaving' under the 'restricted hours' schedule agreement represents large savings for RMOC. But penalty is also large for using electricity during the predetermined restricted hours: the demand penalty amounts to $13.43 per kW in summer ($18.39 per kW in winter) and the consumption penalty amounts to $0.0384 per kW.h in summer ($0.0440 per kW.h in winter). Avoidance of penalty charges is another incentive for pump scheduling and reservoir releases optimization. In the models, this is built in the Level II optimization when creating the pump schedule. 'Fine tuning', especially to limit pumping during restricted hours to avoid penalty, requires operators' knowledge and experience. Thu this aspect is not dealt with in depth at this point: the modelling tools are designed but the results are not truly optimized. Other aspects of optimization, namely better water demand forecasting with time series analyses and the development of actual pump efficiency curves, are again strongly recommended for these branches.

6.3.1 Carlington Heights Branch

The Carlington Heights branch is characterized by its water supply to two minor branches (Hurdman Bridge and Billings Bridge branches) and also to its own water consumption zone (C1W, 36% of the total for RMOC). Also, the reservoir volume is quite large (109.1 ML) of which only 40.6 ML is used in the day-to-day operations. Another characteristic is the use of the 'effective' LI1W+FS1W pumping station with a three-pump scheme from FS1W pumps, which are turbine pumps run from the head differential with the Ottawa River. One drawback from the use of the three-pump scheme is the complex day-to-day operations in the winter time when water demand is lower, as shown from results from Levels I and II optimizations for the winter day control interval (CH2W *offline*). The power consumption factors and discharges (U_m and Q) used for the 'effective' pumping station are as follows: the power factor and discharge from LI1W pumps are used for pumping and the treatment power factor and the total discharge for a particular pump combination are used for treatment; the two are then added. For the FS1W pumping station, only the treatment part is used.

Another peculiarity is the fact that the reservoir cannot be filled to its maximum value on a typical summer day due to the limitation in treatment capacity at the Lemieux Island WPP. The analyses performed in the preceding chapter tackle this aspect in depth (no water is drawn from the R1W reservoir to the 2W zone). For full optimization under present conditions, an increase of 2.5% in treatment capacity is necessary. Because of the power consumption factor and discharge associated with the new pump combinations that can be introduced with increases in the treatment capacity, only increases of 2.5%, 5.0% and 15.0% produce savings in the daily energy costs at the WPPs' pumping stations under present water consumption conditions. Extrapolating for the entire summer period of 183 days and assuming a conservative 60% of this value during the winter, these respective increases translate into yearly savings of $3 355.49, $17 222.50 and $26 135.33. There are construction costs associated with increasing the treatment capacity at the Lemieux Island WPP which are difficult to evaluate but, as for construction costs associated with increasing reservoir storage, they are expected to far exceed the economic advantage of the lower daily energy costs. Therefore, the lower energy costs would serve to dampen construction costs and other factors would need to be identified to justify the costs.

With increasing water demand, the opportunity for optimization under present treatment capacity will decrease, thus the energy costs function will have a steeper slope than if treatment capacity was increased. For an increase of 15.0% in pipe constraint and increases of 10.0%, 20.0% and 30.0% in water demand, we obtain yearly savings of respectively $47 319.41, $73 507.44 and $99 092.30 compared with keeping the present treatment capacity (method of extrapolation from a typical summer day to yearly savings is mentioned previously). Also, a larger treatment capacity would permit a larger operating volume in the Billings Bridge branch.

6.3.2 Glen Cairn/Stittsville Branch

The Glen Cairn/Stittsville branch is characterized by its water supply to the Barrhaven sub-branch and to its own water consumption zone (C2W, 23% of the total for RMOC). This branch also operates two 'effective' reservoirs: R2W (Glen Cairn reservoir and Stittsville elevated tank) and RBAR (one reservoir). In actual operations, water from the RBAR reservoir is pumped to CBAR zone but in special cases, it can be supplied to the C2W zone. Another peculiarity is the fact that the CH2W pumping station makes a link between the 1W zone and the 2W zone, permitting water to be pumped from all four WPPs' pumping stations to C2W (and CBAR) if necessary.

Analyses to determine the 'real' cost of pumping water from the CH2W pumping station demonstrate that the daily energy costs are lower with CH2W *offline* both for summer and winter (savings of $188.85 and $51.92 respectively). Therefore, this pumping station will keep its original purpose: emergency needs and pressure requirements. The only pumping station supplying water to the distribution system is Britannia WPP's BR2W. All possible pump combinations from BR2W can be used, there is no limitation from pipe size and water velocity. Results from Levels I and II optimizations are not more complex than with CH2W *online*, with no more than two pumps selected by the model for each control interval. Also, this facilitates the filling of the R1W reservoir in the Carlington Heights branch since no water can be drawn from the CH2W pumping station.

Two other analyses are performed in this branch: the impact of increasing the operating volume and the impact of increasing the water demand. Results from the first analysis show that the daily energy costs will decrease with an increase in operating volume. For example, increases of 11.2426 ML and 22.4853 ML of operating volume will translate into yearly savings in energy costs of $45 382.58 and $89 559.76 respectively (year data obtained from extrapolation from a typical summer day times 183 days plus from a typical winter day times 182 days). In terms of energy costs per unit operating volume, the costs tend to level off near the maximum increase of 28.1066 ML (corresponding to the maximum pumping capacity of BR2W from a simple water balance). The maximum benefits are in the first increase of 5 ML. For increases of up to 10 ML, it might be possible to increase the operating volume by lowering the safety coefficient on the lowest possible volume that can remain in the reservoir. This should only be done after studies are undertaken to evaluate the impact of doing so. The high construction costs involved for an increase of operating volume of 15 ML and up cannot be justified from the savings in energy costs. Again, if there is a need identified by factors other than economic, savings in energy costs will serve to dampen the high construction costs.

As water demand increases, daily energy costs will increase steadily but will be lower for a larger operating volume. From simple water balances, it becomes obvious that with an increase in water demand, there is less water available to fill a reservoir at night. Therefore, when determining the size of operating volume of a reservoir for optimization of energy costs, care should be taken to evaluate the impact of increasing water demand.

Table 6.1 summarizes the potential energy savings at the WPPs as identified in the discussion for different water management alternatives. These savings are calculated from the impact of implementing the water management alternative (increasing operating volumes, pipe constraints, and water demands) compared to present conditions.

CHAPTER 7

CONCLUSIONS

The first objective of this study was to design a computer model to optimize pump scheduling and reservoir releases for the Regional Municipality of Ottawa-Carleton's (RMOC) water supply system. The mathematical formulation chosen was linear programming (LP). The model was developed successfully with the use of a *Borland's* Quattro Pro spreadsheet and its built-in LP solver called 'Optimizer'.

The results obtained for the minor branches and the sub-branch could not be directly compared with hydro bills from the minor pumping stations to identify potential savings from the improved pump scheduling and reservoir releases. Nevertheless they have a direct impact on the energy costs in the major branches, where the water purification plants are under Ottawa Hydro's *restricted* hours agreement.

From the compilation of energy costs at the WPPs for both summer and winter typical days, it is clear that the results obtained are 'realistic' although the model has not been calibrated. A major difference between actual and optimized operations is the fact that the model output favors pumping water from LI1W+FS1W and FS1W pump combinations and less from BR1W: hence the 'large' savings at Britannia WPP and the 'large' increase in cost at Lemieux Island WPP. These differences highlight the need to reexamine the treatment power consumption factor at Lemieux Island WPP. Also, since the model favors those pump combinations, the Lemieux Island WPP treatment capacity becomes even more of a limitation since it prevents the Carlington Heights reservoir to be filled at night.

Full optimization (reservoir full at night) is not possible for a typical summer day and therefore will not be possible as water demand increases in the future. This gives an example of how the development of an operations optimization model, although from historical data and not in real-time, can help to identify areas where operations could be improved.

The second objective of this study was to analyze different water management alternatives for RMOC's system. It is clear from those analyses that RMOC can optimize pump scheduling and reservoir releases under present conditions, but full optimization will not be possible with increasing water demand. Although far from compromising its security of supply to the consumers, different water management alternatives have to be studied in order to control future energy costs. The alternatives highlighted by this study are: (i) increasing operating volumes in the Billings Bridge and the Glen Cairn/Stittsville branches; (ii) increasing the treatment capacity at the Lemieux Island WPP; and (iii) considering a larger pipe size and additional smaller pumps in the Hurdman Bridge branch. All these alternatives involve construction except for slight increases in operating volume that can be achieved by reevaluating safety coefficients on the minimum allowable reservoir storage volume. The benefits of these alternatives reside in the simpler and more economical day-to-day operations.

The increase of Billings Bridge branch operating volume actually translates into building new storage facilities since the only one present at the moment is an elevated storage tank for pressure requirements. Although it would simplify day-to-day operations, construction costs could not be justified from an economical view point. More data on expected change in population and land uses for the near future in this water demand area are needed to assess the need for additional storage.

The increase in operating volume in the Glen Cairn/Stittsville branch is found to be beneficial if it comes from lowering the minimum allowable water volume in the reservoir. Again, a detailed study of historical data and operations of both the Glen Cairn reservoir and the Stittsville elevated tank is needed before a decision is made to lower the safety coefficient on the minimum water volume.

As discussed above, increasing the treatment capacity at the Lemieux Island WPP is the main area of improvement highlighted in this study. As for the Hurdman Bridge branch, the pumping capacity is high but the pipe size is very limiting. As water demand increases the possibility for full optimization will slowly decrease.

Population is expected to grow by 29% from 1991 to 2011 in Ottawa-Carleton (RMOC, 1994), increasing the demands and stresses on our natural resources. Water has always been considered as an endless renewable resource and therefore, is greatly undervalued. As water quality deteriorates due to pollution, the treatment costs will rise. As water demand increases due to the larger population and industrial development, the operating costs and infrastructure costs will rise. Optimization of pump scheduling and reservoir releases is an essential part of the global optimization of municipal water supply which includes better demand forecasting, optimization of the water treatment process, etc. It is not only time to optimize water supply costs but also to start managing demand. RMOC has unemployment rates well below provincial and national rates and the workforce is highly educated (in 1991, 23% of people over the age of 15 had a university degree, i.e. twice the national average; RMOC, 1994). These characteristics of the population offer incredible advantages in terms of education and implementation of water demand management programs.

CHAPTER 8

RECOMMENDATIONS FOR FUTURE RESEARCH

Detailed studies within RMOC are needed to reevaluate the treatment power consumption factor for the Lemieux Island WPP and the minimum allowable water volume for the different storage reservoirs in the network. Actual head/discharge and power/discharge curves need to be developed for individual pumps and pump combinations. Also, changes in population and land uses for the near future in the different water demand zones should be carefully monitored and incorporated in the model to assess their impact on the operations.

Thorough studies are needed to develop better demand forecasting modules (possibly using time series analysis) and to optimize the water treatment process. Also, water audits could be performed for large water users (industries, government buildings, universities, apartment complexes, etc.) in order to identify areas where "Reduce, Reuse, Recycle" could be implemented for water.

Ultimately, advances in affordable and reliable technology will permit the design of a real-time operations model with a computerized control centre that would incorporate real-time data obtained by telemetry. More complex mathematical formulation (less need for simplification) and problem solving techniques could be used if the data collection was dependable and extensive.

CHAPTER 9

APPENDICES

APPENDIX A: TABLES

APPENDIX B: FIGURES

APPENDIX C: MODELS

APPENDIX D: OTTAWA HYDRO RATES AND WPPS' BILLS

APPENDIX A

TABLES

Table 1.1 - Population and Area of RMOC's Municipalities and Sub-Areas (1991)

Municipality	Population (in 1000's)	Area (ha)
Ottawa	313.99	11015
Vanier	18.15	293
Rockcliffe Park	2.12	174
Cumberland	40.70	31569
Gloucester	101.68	29386
Goulbourn	16.16	27132
Kanata	37.34	13219
Nepean	107.63	21702
Osgoode	13.98	37986
Rideau	11.78	40875
West Carleton	14.65	62347
Total RMOC	678.15	275698
Sub-Areas	**Area (ha)**	
Inside Greenbelt	19250	
Kanata (West Urban Centre)	3425	
Orléans (East Urban Centre)	4820	
Stittsville	1215	
Barrhaven (South Urban Centre)	550	
Blackburn Hamlet	240	
Bell's Corners	390	

(Source: RMOC, 1993)

Table 1.2 - Ottawa Hydro 1993 Electricity Rates Used in the Model

Periods	Summer (July)			Winter (January)		
	Hours of the day	Description	Unit Cost ($/kW.h)	Hours of the day	Description	Unit Cost ($/kW.h)
1	23 to 7	Off-Peak	0.0237	23 to 7	Off-Peak	0.0345
2	7 to 10	Peak	0.0713	7 to 9	Peak	0.0863
3	10 to 16	Restriction	0.0713	**9 to 11**	**Restriction**	**0.0863**
4	16 to 23	Peak	0.0713	11 to 16:30	Peak	0.0863
5				**16:30 to 19**	**Restriction**	**0.0863**
6				19 to 23	Peak	0.0863

[shaded box] : indicates possibility for penalty for July and January

Table 1.3 - Restricted Hours Schedule Throughout the Year

Period		Time of Daily Restriction (EST)			
From	To	From	To	From	To
January 1	Jan. 31	9:00	11:00	16:30	19:00
February 1	Feb. 28	8:00	11:00	16:30	19:00
March 1	April 3	8:00	12:00	16:30	19:30
April 4	May 31	8:00	14:00	-	-
June 1	Sept. 30	10:00	16:00	-	-
October 1	Oct. 30	8:00	10:30	16:30	18:30
October 31	Dec. 31	8:00	12:00	16:30	18:30

Table 4.1 - Hurdman Bridge Branch Electrical Pump Combinations (HB1E)

m	Pump Code	Capacity (ML/d)	Qm (ML/h)	Electrical Consumpt. (kW)	Um (kW.h/ML)
1	E;D	92.7	3.8625	373	96.57
2	EE;ED;DD	185.4	7.7250	746	96.57

Table 4.2 - Hurdman Bridge Branch Reservoir Operations Characteristics (R1E)

Season	Total Volume [Max] (ML)	Operating Volume (ML)	Remaining Volume [Min] (ML)	Fill/Empty Pipe Capacity (ML/d)	Fixed Valve Constraint (ML/d)	Fixed Valve Constraint (ML/h)
Summer	89.7	37.8	51.9	206.0	200.0	8.3333
Winter	89.7	48.0	41.7	206.0	200.0	8.3333

Table 4.3 - Billings Bridge Branch Electrical Pump Combinations (BB2C)

m	Pump Code	Capacity (ML/d)	Qm (ML/h)	Electrical Consumpt. (kW)	Um (kW.h/ML)
1	S	19.6	0.8167	131	160.41
2	B	37.3	1.5542	224	144.13
3	SS	39.2	1.6333	262	160.41
4	SB	56.9	2.3708	355	149.74
5	BB	74.6	3.1083	448	144.13
6	SSB	76.5	3.1875	486	152.47
7	SBB	94.2	3.9250	579	147.52
8	BBB	111.9	4.6625	672	144.13
9	SSBB	113.8	4.7417	710	149.74

Table 4.4 - Billings Bridge Branch Reservoir Operations Characteristics (R2C)

Season	Total Volume [Max] (ML)	Operating Volume (ML)	Remaining Volume [Min] (ML)	Fill/Empty Pipe Capacity (ML/d)	Fixed Valve Constraint (ML/d)	Fixed Valve Constraint (ML/h)
Summer	3.4	1.1	2.3	37.9	37.0	1.5417
Winter	3.4	0.9	2.5	37.9	37.0	1.5417

Table 4.5a - Carlington Heights Branch Britannia 1W Pumps (BR1W)

Pumps	Speed (rpm)	Capacity (ML/d)	Head (m)	Electrical Consumpt. (HP - kW)	Diesel Consumpt. (HP - kW)	Optimizat. Pump Code
PD-1	900	95.5	65.5	1575-1175	1575-1175	B
PE-3	900	63.6	65.5	800 - 597	n/a	E
PE-5	1175	31.8	65.5	450 - 336	n/a	S
PD/PE-7	890	63.6	65.5	900 - 671	900 - 672	D

Table 4.5b - Carlington Heights Branch Lemieux Island 1W Pumps (LI1W)

Pumps	Speed (rpm)	Capacity (ML/d)	Head (m)	Electrical Consumpt. (HP - kW)	Diesel Consumpt. (HP - kW)	Optimizat. Pump Code
E-1	720	136.1	64.0	1500-1119	n/a	B
E/D-2	880	136.1	64.0	1500-1119	1500-1121	B
E-3	900	95.0	64.0	950 - 709	n/a	E
E-4	900	95.0	64.0	950 - 709	n/a	E

Table 4.5c - Carlington Heights Branch Fleet Street 1W Pumps (FS1W)

Pumps	Speed (rpm)	Capacity (ML/d)	Head (m)	Electrical Consumpt. (HP - kW)	Diesel Consumpt. (HP - kW)	Optimizat. Pump Code
T-1	constant	76.9	55.5	760 - 567	n/a	B
T-2	constant	27.2	59.7	300 - 224	n/a	S
T-3	constant	27.2	59.7	300 - 224	n/a	S
T-4	constant	27.2	59.7	300 - 224	n/a	S
T-5	constant	76.9	55.5	760 - 567	n/a	B

Table 4.6 - Carlington Heights Branch Electrical Pump Combinations
(BR1W, LI1W, FS1W)

Pumping Station	m	Pump Code	Capacity (ML/d)	Qm (ML/h)	Electrical Consumpt. (kW)	Um (kW.h/ML)
BR1W	1	E	63.6	2.6500	597	225.28
	2	S	31.8	1.3250	336	253.58
	3	D	63.6	2.6500	671	253.21
	4	ES	95.4	3.9750	933	234.72
	5	ED	127.2	5.3000	1268	239.25
	6	SD	95.4	3.9750	1007	253.33
	7	ESD	159.0	6.6250	1604	242.11
LI1W+FS1W	8	BBS-E	276.0	11.5000	709	179.12
	9	BSS-B	267.4	11.1417	1119	197.33
	10	BSS-E	226.3	9.4292	709	179.12
	11	SSS-B	217.7	9.0708	1119	197.33
	12	SSS-E	176.6	7.3583	709	179.12
	13	SSS-EE	271.6	11.3167	1418	179.12
	14	BSSS-E	253.5	10.5625	709	179.12
FS1W	15	BBS	181.0	7.5417	0	0.00
	16	BSS	131.3	5.4708	0	0.00
	17	SSS	81.6	3.4000	0	0.00
	18	BBSS	208.2	8.6750	0	0.00
	19	BSSS	158.5	6.6042	0	0.00
	20	BBSSS	235.4	9.8083	0	0.00

Table 4.7 - Carlington Heights Branch Reservoir Operations Characteristics (R1W)

Season	Total Volume [Max] (ML)	Operating Volume (ML)	Remaining Volume [Min] (ML)	Fill/Empty Pipe Capacity (ML/d)	Fixed Valve Constraint (ML/d)	Fixed Valve Constraint (ML/h)
Summer	109.1	40.6	68.5	151.3/189.2	150.0	6.2500
Winter	109.1	40.6	68.5	151.3/189.2	150.0	6.2500

Table 4.8a - Glen Cairn/Stittsville Branch Britannia 2W Pumps (BR2W)

Pumps	Speed (rpm)	Capacity (ML/d)	Head (m)	Electrical Consumpt. (HP - kW)	Diesel Consumpt. (HP - kW)	Optimizat. Pump Code
PD-2	900	90.0	78.0	1750-1305	1750-1305	D
PE-4	900	90.0	78.0	1350-1007	n/a	E
PE-6	1200	45.0	78.0	750 - 560	n/a	S
PD/PE-8	892	97.0	81.0	1500-1119	1500-1121	B

Table 4.8b - Glen Cairn/Stittsville Branch Carlington Heights 2W Pumps (CH2W)

Pumps	Speed (rpm)	Capacity (ML/d)	Head (m)	Electrical Consumpt. (HP - kW)	Diesel Consumpt. (HP - kW)	Optimizat. Pump Code
PE-1	constant	16.4	43.0	125 - 93	n/a	S
PE-2	constant	16.4	43.0	125 - 93	n/a	S
PDD-3	constant	25.2	43.0	200 - 149	264 - 197	B
PE-4	constant	25.2	43.0	200 - 149	n/a	B

Table 4.9 - Glen Cairn/Stittsville Branch Electrical Pump Combinations (BR2W, CH2W)

Pumping Station	m	Pump Code	Capacity (ML/d)	Qm (ML/h)	Electrical Consumpt. (kW)	Um (kW.h/ML)
BR2W	1	E	90.0	3.7500	1007	268.53
	2	S	45.0	1.8750	560	298.67
	3	B	97.0	4.0417	1119	276.87
	4	ES	135.0	5.6250	1567	278.58
	5	EB	187.0	7.7917	2126	272.86
	6	SB	142.0	5.9167	1679	283.77
	7	ESB	232.0	9.6667	2686	277.86
CH2W	8	S	16.4	0.6833	93	136.10
	9	B	25.2	1.0500	149	141.90
	10	SS	32.8	1.3667	186	136.10

Table 4.10 - Barrhaven Sub-Branch Pumps (BHPS)

Pumps	Speed (rpm)	Capacity (ML/d)	Head (m)	Electrical Consumpt. (HP - kW)	Diesel Consumpt. (HP - kW)	Optimizat. Pump Code
PED-1	variable	11.0	55.0	125 - 93	?	D
PED-2	variable	34.6	38.0	350 - 261	361 - 270	B
P-3	variable	17.3	38.0	200 - 149	n/a	E
P-4	variable	17.3	38.0	200 - 149	n/a	E
PE-5	constant	4.5	30.5	40 - 30	n/a	S

Table 4.11 - Barrhaven Sub-Branch Electrical Pump Combinations (BHPS)

Pumping Station	m	Pump Code	Capacity (ML/d)	Qm (ML/h)	Electrical Consumpt. (kW)	Um (kW.h/ML)
BHPS	1	D	11.0	0.4583	93	202.91
	2	B	34.6	1.4417	261	181.04
	3	E	17.3	0.7208	149	206.71
	4	S	4.5	0.1875	30	160.00
	5	DB	45.6	1.9000	354	186.32
	6	DE	28.3	1.1792	242	205.23
	7	DS	15.5	0.6458	123	190.45
	8	BS	39.1	1.6292	291	178.62
	9	ES	21.8	0.9083	179	197.06
	10	EE	34.6	1.4417	298	206.71
	11	DES	32.8	1.3667	272	199.02
	12	DEE	45.6	1.9000	391	205.79
	13	EES	39.1	1.6292	328	201.33

Table 4.12a - Glen Cairn/Stittsville Branch Reservoir Operations Characteristics (R2W)

Season	Total Volume [Max] (ML)	Operating Volume (ML)	Remaining Volume [Min] (ML)	Fill/Empty Pipe Capacity (ML/d)	Fixed Valve Constraint (ML/d)	Fixed Valve Constraint (ML/h)
Summer	38.7	14.9	23.8	168.1	165.0	6.8750
Winter	38.7	14.6	24.1	168.1	165.0	6.8750

Table 4.12b - Barrhaven Sub-Branch Reservoir Operations Characteristics (RBAR)

Season	Total Volume [Max] (ML)	Operating Volume (ML)	Remaining Volume [Min] (ML)	Fill/Empty Pipe Capacity (ML/d)	Fixed Valve Constraint (ML/d)	Fixed Valve Constraint (ML/h)
Summer	19.5	12.7	6.8	59.1	58.0	2.4167
Winter	19.5	12.7	6.8	59.1	58.0	2.4167

Table 4.13 - Electricity Rates: Step Functions for Peak Usage

Ottawa Hydro					**City of Nepean**	
"G.S. Time-Of-Use"			**"General Service"**			
All year	Summer	Winter	Summer and Winter		Summer and Winter	
Blocks (kW.h)	**Unit Cost** ($/kW.h)	**Unit Cost** ($/kW.h)	**Blocks** (kW.h)	**Unit Cost** ($/kW.h)	**Blocks** (kW.h)	**Unit Cost** ($/kW.h)
250	0.1040	0.1261	250	0.0803	250	0.102
6625	0.1019	0.1256	12250	0.0765	12250	0.0749
1184000	0.0713	0.0863	1983900	0.0562	2129000	0.0554
All addn	0.0406	0.0469	All addn	0.0358	All addn	0.0358

Table 4.14 - Example of Hourly Coefficients for Selected Pump Combinations
(Glen Cairn/Stittsville Branch for a Typical Summer Night)

Hour of the day	BR2W X1 (E)	BR2W X5 (EB)	Constraints	
			Sum(X)=1	XQ-Vk>=0
23:00	0.0000	1.0000	1.0000	3.5938
24:00	0.6486	0.3514	1.0000	1.7037
1:00	0.6486	0.3514	1.0000	2.4583
2:00	0.6486	0.3514	1.0000	2.8066
3:00	0.6486	0.3514	1.0000	2.9183
4:00	0.6486	0.3514	1.0000	3.0262
5:00	0.0000	1.0000	1.0000	5.7300
6:00	0.0000	1.0000	1.0000	5.3633
Total =	3.2428	4.7572	F(X) =	0.0001
Check:	3.2429	4.7571		Yes

Table 4.15 - Example of Hourly Water Balance or Pump Schedule
(Glen Cairn/Stittsville Branch for a Typical Summer Night)

Hour during control interval	Water Pumped BR2W XQ (ML)	Water Pumped CH2W XQ (ML)	Water Consumpt. C2W Vk (ML)	Water Consumpt. CBAR Vk (ML)	Water into both Reservoirs (ML)	Flow Rate into both Reservoirs (ML/d)
23	7.7917	0.0000	3.8513	0.3467	3.5938	86.3
24	5.1704	0.0000	3.2208	0.2458	1.7037	40.9
1	5.1704	0.0000	2.5467	0.1654	2.4583	59.0
2	5.1704	0.0000	2.2258	0.1379	2.8066	67.4
3	5.1704	0.0000	2.1204	0.1317	2.9183	70.0
4	5.1704	0.0000	2.0158	0.1283	3.0262	72.6
5	7.7917	0.0000	1.9333	0.1283	5.7300	137.5
6	7.7917	0.0000	2.2588	0.1696	5.3633	128.7
Total =	49.2269	0.0000	20.1729	1.4538	27.6002	
Check:	49.2268	0.0000	20.1729	1.4538	27.6001	

Table 5.1 - Hurdman Bridge Pump Schedule for a Typical Summer Night

Hour during control interval	Pumps Required	Water Pumped XQ (ML)	Water Consumpt. Vk (ML)	Water to fill Reservoir (ML)	Flow Rate into Reservoir (ML/day)
23	2 pumps	7.7250	4.5342	3.1908	76.6
24	2 pumps	7.7250	3.6329	4.0921	98.2
1	2 pumps	7.7250	2.6733	5.0517	121.2
2	2 pumps	7.7250	2.3038	5.4213	130.1
3	2 pumps	7.7250	2.1413	5.5838	134.0
4	2 pumps	7.7250	2.1913	5.5338	132.8
5	2 pumps	7.7250	2.1917	5.5333	132.8
6	2 then 1	6.1346	2.7413	3.3933	81.4
	Total =	60.2096	22.4096	37.8000	
	Check:	60.2096	22.4096	37.8000	

Table 5.2 - Hurdman Bridge Pump Schedule for a Typical Summer Day

Hour during control interval	Pumps Required	Water Pumped XQ (ML)	Water Consumpt. Vk (ML)	Water from Reservoir (ML)	Flow Rate from Reservoir (ML/day)	
7	1 pump	3.8625	4.1413	0.2788	6.7	
8	1 pump	3.8625	5.1408	1.2783	30.7	
9	1 pump	3.8625	5.4629	1.6004	38.4	
10			6.1500	6.1500	147.6	
11			6.4796	6.4796	155.5	RESTRICTION
12			5.9517	5.9517	142.8	PERIOD
13	1 pump*	3.7245	5.5429	1.8184	43.6	@ WPPs
14	1 pump	3.8625	5.1854	1.3229	31.7	
15	1 pump	3.8625	5.0379	1.1754	28.2	
16	1 pump	3.8625	4.9383	1.0758	25.8	
17	1 pump	3.8625	5.0625	1.2000	28.8	
18	1 pump	3.8625	5.4746	1.6121	38.7	
19	1 pump	3.8625	5.8875	2.0250	48.6	
20	1 pump	3.8625	5.9954	2.1329	51.2	
21	1 pump	3.8625	5.9988	2.1363	51.3	
22	1 pump	3.8625	5.4250	1.5625	37.5	
	Total =	50.0745	87.8746	37.8000		
	Check:	50.0745	87.8746	37.8000		

Table 5.3 - Hurdman Bridge Pump Schedule for a Typical Winter Night

Hour during control interval	Pumps Required	Water Pumped XQ (ML)	Water Consumpt. Vk (ML)	Water to fill Reservoir (ML)	Flow Rate into Reservoir (ML/day)
23	2 pumps	7.7250	3.6775	4.0475	97.1
24	2 pumps	7.7250	3.0100	4.7150	113.2
1	2 pumps	7.7250	2.5467	5.1783	124.3
2	2 pumps	7.7250	2.2854	5.4396	130.6
3	2 pumps	7.7250	2.1054	5.6196	134.9
4	2 pumps	7.7250	2.1092	5.6158	134.8
5	2 pumps	7.7250	2.2217	5.5033	132.1
6	2 pumps	7.7250	2.4596	5.2654	126.4
	Total =	61.8000	20.4154	41.3846	
	Check:	61.8000	20.4154	41.3846	

Table 5.4 - Hurdman Bridge Pump Schedule for a Typical Winter Day

Hour during control interval	Pumps Required	Water Pumped XQ (ML)	Water Consumpt. Vk (ML)	Water from Reservoir (ML)	Flow Rate from Reservoir (ML/day)	
7		0.0000	3.6279	3.6279	87.1	
8	1 pump	3.8625	4.5296	0.6671	16.0	
9		0.0000	4.3279	4.3279	103.9	RESTRICTION
10		0.0000	4.5250	4.5250	108.6	PERIOD
11		0.0000	4.6017	4.6017	110.4	
12	1 pump	3.8625	4.6046	0.7421	17.8	
13	1 pump	3.8625	4.3725	0.5100	12.2	
14	1 pump	3.8625	4.1704	0.3079	7.4	
15		0.0000	3.9504	3.9504	94.8	
16		0.0000	3.9892	3.9892	95.7	RESTRICTION
17		0.0000	4.1204	4.1204	98.9	PERIOD
18		0.0000	4.4183	4.4183	106.0	@ WPPs
19	1 pump*	0.3925	4.6404	4.2479	102.0	
20	1 pump	3.8625	4.5817	0.7192	17.3	
21	1 pump	3.8625	4.2942	0.4317	10.4	
22	1 pump	3.8625	4.0604	0.1979	4.7	
	Total =	27.4300	68.8146	41.3846		
	Check:	27.4300	68.8146	41.3846		

Table 5.5a - Billings Bridge Pump Schedule for a Typical Summer Night

Hour during control interval	Pumps Required	Water Pumped XQ (ML)	Water Consumpt. Vk (ML)	Water into Reservoir (ML)	Flow Rate into Reservoir (ML/day)
1	B then S	1.4067	1.2908	0.1158	2.8
2	B then S	1.4067	1.3121	0.0946	2.3
3	B then S	1.4067	1.1283	0.2783	6.7
4	B then S	1.4067	1.1479	0.2588	6.2
5	B then S	1.4067	1.2300	0.1767	4.2
6	B then S	1.4067	1.2308	0.1758	4.2
	Total =	8.4400	7.3400	1.1000	
	Check:	8.4400	7.3400	1.1000	

Table 5.5b - Billings Bridge Hourly Coefficients for a Typical Summer Night

Hour of			Constraints	
the day	X2 (B)	X1 (S)	Sum(X)=1	XQ-Vk>=0
1:00	0.8000	0.2000	1.0000	0.1158
2:00	0.8000	0.2000	1.0000	0.0946
3:00	0.8000	0.2000	1.0000	0.2783
4:00	0.8000	0.2000	1.0000	0.2588
5:00	0.8000	0.2000	1.0000	0.1767
6:00	0.8000	0.2000	1.0000	0.1758
Total =	4.8000	1.2000	F(X) =	0.0001
Check:	4.8000	1.2000		Yes

Table 5.6a - Billings Bridge Pump Schedule for a Typical Summer Day

Hour during control interval	Pumps Required	Water Pumped XQ (ML)	Water Consumpt. Vk (ML)	Water from Reservoir (ML)	Flow Rate from Reservoir (ML/day)	
7		1.9492	1.9492	0.0000	0.0	
8	ALL	2.4658	2.4658	0.0000	0.0	
9		2.7317	2.7317	0.0000	0.0	
10		2.6822	2.9825	0.3003	7.2	
11		2.6822	3.1454	0.4632	11.1	RESTRICTION
12	THREE	2.6822	2.8317	0.1494	3.6	PERIOD
13	PUMPS	2.6537	2.6538	0.0000	0.0	@ WPPs
14		2.5384	2.5383	0.0000	0.0	
15		2.5105	2.5104	0.0000	0.0	
16		2.3771	2.3771	0.0000	0.0	
17		2.5355	2.5354	0.0000	0.0	
18	AT	2.6759	2.6758	0.0000	0.0	
19	EACH	2.6827	2.7504	0.0677	1.6	
20	HOUR	2.6827	2.7554	0.0727	1.7	
21		2.6484	2.6600	0.0116	0.3	
22		2.5005	2.5358	0.0353	0.8	
23		2.1175	2.1175	0.0000	0.0	
24		1.8742	1.8742	0.0000	0.0	
	Total =	44.9904	46.0904	1.1000		
	Check:	44.9904	46.0904	1.1000		

Table 5.6b - Billings Bridge Hourly Coefficients for a Typical Summer Day

Hour of the day	X8 (BBB)	X5 (BB)	X2 (B)	Constraints Sum(X)<=1	XQ-Vk<=0	
7:00	0.0487	0.3115	0.4852	0.8454	-0.0000	
8:00	0.1647	0.3037	0.4852	0.9536	-0.0000	
9:00	0.2309	0.2958	0.4734	1.0000	-0.0000	
10:00	0.2111	0.3037	0.4852	1.0000	-0.3003	
11:00	0.2111	0.3037	0.4852	1.0000	-0.4632	RESTRICTION
12:00	0.2111	0.3037	0.4852	1.0000	-0.1494	PERIOD
13:00	0.2050	0.3037	0.4852	0.9939	-0.0000	@ WPPs
14:00	0.1802	0.3037	0.4852	0.9692	0.0000	
15:00	0.1742	0.3037	0.4852	0.9632	0.0000	
16:00	0.1456	0.3037	0.4852	0.9346	-0.0000	
17:00	0.1796	0.3037	0.4852	0.9685	0.0000	
18:00	0.2097	0.3037	0.4852	0.9987	0.0000	
19:00	0.2112	0.3037	0.4852	1.0000	-0.0677	
20:00	0.2112	0.3037	0.4852	1.0000	-0.0727	
21:00	0.2038	0.3037	0.4852	0.9927	-0.0116	
22:00	0.1721	0.3037	0.4852	0.9610	-0.0353	
23:00	0.0900	0.3037	0.4852	0.8789	-0.0000	
24:00	0.0378	0.3037	0.4852	0.8267	-0.0000	
Total =	3.0978	5.4662	8.7225	F(X) =	0.0001	
Check:	3.0978	5.4662	8.7225		Yes	

Table 5.7 - Billings Bridge Pump Schedule for a Typical Winter Night

Hour during control interval	Pumps Required	Water Pumped XQ (ML)	Water Consumpt. Vk (ML)	Water into Reservoir (ML)	Flow Rate into Reservoir (ML/day)
1	S	0.8167	0.6604	0.1563	3.8
2	S	0.8167	0.6504	0.1663	4.0
3	S	0.8167	0.5188	0.2979	7.2
4	S	0.8167	0.6008	0.2158	5.2
5	S	0.8167	0.5308	0.2858	6.9
6	S	0.8167	0.7658	0.0508	1.2
	Total =	4.9000	3.7271	1.1729	
	Check:	4.9000	3.7271	0.9000	

Table 5.8a - Billings Bridge Pump Schedule for a Typical Winter Day

Hour during control interval	Pumps Required	Water Pumped XQ (ML)	Water Consumpt. Vk (ML)	Water from Reservoir (ML)	Flow Rate from Reservoir (ML/day)	
7		1.4775	1.4775	0.0000	0.0	
8	ALL	2.0700	2.0700	0.0000	0.0	
9		2.1496	2.1496	0.0000	0.0	RESTRICTION
10		2.1275	2.1275	0.0000	0.0	PERIOD
11		1.5542	2.2517	0.6975	16.7	@ WPPs
12	TWO	2.1142	2.1142	0.0000	0.0	
13	PUMPS	2.1250	2.1250	0.0000	0.0	
14		1.8463	1.8463	0.0000	0.0	
15		1.8421	1.8421	0.0000	0.0	
16		1.5544	1.5854	0.0311	0.7	RESTRICTION
17		1.8964	1.9125	0.0161	0.4	PERIOD
18	AT	1.8923	1.9233	0.0311	0.7	@ WPPs
19	EACH	2.0352	2.0663	0.0311	0.7	
20	HOUR	1.9977	2.0288	0.0311	0.7	
21		1.7444	1.7754	0.0311	0.7	
22		1.6614	1.6925	0.0311	0.7	
23		1.3958	1.3958	0.0000	0.0	
24		1.1388	1.1388	0.0000	0.0	
	Total =	32.6226	33.5225	0.9000		
	Check:	32.6225	33.5225	0.9000		

Table 5.8b - Billings Bridge Hourly Coefficients for a Typical Winter Day

Hour of the day	X5 (BB)	X2 (B)	Constraints Sum(X)<=1	XQ-Vk<=0	
7:00	0.0000	0.9507	0.9507	-0.0000	
8:00	0.3319	0.6681	1.0000	0.0000	
9:00	0.3831	0.6169	1.0000	0.0000	RESTRICTION PERIOD
10:00	0.3689	0.6311	1.0000	-0.0000	
11:00	0.0000	1.0000	1.0000	-0.6975	
12:00	0.3603	0.6397	1.0000	0.0000	
13:00	0.3673	0.6327	1.0000	0.0000	
14:00	0.1879	0.8121	1.0000	0.0000	
15:00	0.1853	0.8147	1.0000	0.0000	
16:00	0.0001	0.9999	1.0000	-0.0311	RESTRICTION PERIOD @ WPPs
17:00	0.2202	0.7798	1.0000	-0.0161	
18:00	0.2176	0.7824	1.0000	-0.0311	
19:00	0.3095	0.6905	1.0000	-0.0311	
20:00	0.2854	0.7146	1.0000	-0.0311	
21:00	0.1224	0.8776	1.0000	-0.0311	
22:00	0.0690	0.9310	1.0000	-0.0311	
23:00	0.0423	0.8135	0.8558	0.0000	
24:00	0.0000	0.7327	0.7327	0.0000	
Total =	3.4512	14.0880	F(X) =	0.0001	
Check:	3.4512	14.0880		Yes	

Table 5.9 - Carlington Heights Pump Schedule for a Typical Summer Night

Hour during control interval	Water Pumped XQ (ML)	Water Pumped to 2C XQ (ML)	Water Pumped to 1E XQ (ML)	Water Pumped to 2W XQ (ML)	Water Consumpt. C1W Vk (ML)	Water into Reservoir (ML)	Flow Rate into Reservoir (ML/day)
23	18.1250	2.1175	7.7250	0.0000	5.6800	2.6025	62.5
24	18.1250	1.8742	7.7250	0.0000	4.8846	3.6413	87.4
1	18.1250	1.4067	7.7250	0.0000	4.4842	4.5092	108.2
2	18.1250	1.4067	7.7250	0.0000	3.8654	5.1279	123.1
3	18.1250	1.4067	7.7250	0.0000	4.0725	4.9208	118.1
4	18.1250	1.4067	7.7250	0.0000	3.7808	5.2125	125.1
5	18.1250	1.4067	7.7250	0.0000	3.6333	5.3600	128.6
6	18.1250	1.4067	6.1346	0.0000	3.9538	6.6300	159.1
Total =	145.0000	12.4317	60.2096	0.0000	34.3546	38.0041	
Check:	145.0000	12.4317	60.2096	0.0000	34.3546	38.0041	

Table 5.10a - Carlington Heights Pump Schedule for a Typical Summer Day

Hour during control interval	Water Pumped XQ (ML)	Water Pumped to 2C XQ (ML)	Water Pumped to 1E XQ (ML)	Water Pumped to 2W XQ (ML)	Water Consumpt. C1W Vk (ML)	Water from Reservoir (ML)	Flow Rate from Reservoir (ML/day)
7	11.4386	1.9492	3.8625	1.3667	5.1125	0.8523	20.5
8	11.4386	2.4658	3.8625	1.3667	6.4646	2.7210	65.3
9	11.4386	2.7317	3.8625	1.3667	6.9442	3.4664	83.2
10	11.4386	2.6822	0.0000	1.3667	7.9271	0.5374	12.9
11	11.4386	2.6822	0.0000	1.3667	8.5283	1.1387	27.3
12	11.4386	2.6822	0.0000	1.3667	7.7538	0.3641	8.7
13	11.4386	2.6537	3.7245	1.3667	7.0408	3.3472	80.3
14	11.4386	2.5384	3.8625	1.3667	6.9446	3.2736	78.6
15	11.4386	2.5105	3.8625	1.3667	6.4358	2.7370	65.7
16	11.4386	2.3771	3.8625	1.3667	6.4858	2.6535	63.7
17	11.4386	2.5355	3.8625	1.3667	6.4846	2.8107	67.5
18	11.4386	2.6759	3.8625	1.3667	6.4483	2.9149	70.0
19	11.4386	2.6827	3.8625	1.3667	6.6729	3.1462	75.5
20	11.4386	2.6827	3.8625	1.3667	6.5171	2.9904	71.8
21	11.4386	2.6484	3.8625	1.3667	6.3638	2.8027	67.3
22	11.4386	2.5005	3.8625	1.3667	5.9567	2.2478	53.9
Total =	183.0168	40.9989	50.0745	21.8667	108.0808	38.0041	
Check:	183.0168	40.9989	50.0745	21.8667	108.0808	38.0041	

RESTRICTION PERIOD @ WPPs

Table 5.10b - Carlington Heights Hourly Coefficients for a Typical Summer Day

Hour of the day	BR1W X1 (E)	FS1W X20(BBSSS)	Constraints (X)<=1	FvTv <=0	
7:00	0.6152	1.0000	1.0000	-0.8523	
8:00	0.6152	1.0000	1.0000	-2.7210	
9:00	0.6152	1.0000	1.0000	-3.4664	
10:00	0.6152	1.0000	1.0000	-0.5374	
11:00	0.6152	1.0000	1.0000	-1.1387	
12:00	0.6152	1.0000	1.0000	-0.3641	RESTRICTION
13:00	0.6152	1.0000	1.0000	-3.3472	PERIOD
14:00	0.6152	1.0000	1.0000	-3.2736	
15:00	0.6152	1.0000	1.0000	-2.7370	
16:00	0.6152	1.0000	1.0000	-2.6535	
17:00	0.6152	1.0000	1.0000	-2.8107	
18:00	0.6152	1.0000	1.0000	-2.9149	
19:00	0.6152	1.0000	1.0000	-3.1462	
20:00	0.6152	1.0000	1.0000	-2.9904	
21:00	0.6152	1.0000	1.0000	-2.8027	
22:00	0.6152	1.0000	1.0000	-2.2478	
Total =	9.8428	16.0000	F (X) =	0.0001	
Check:	9.8428	16.0000		Yes	

Table 5.11 - Carlington Heights Pump Schedule for a Typical Winter Night

Hour during control interval	Water Pumped XQ (ML)	Water Pumped to 2C XQ (ML)	Water Pumped to 1E XQ (ML)	Water Pumped to 2W XQ (ML)	Water Consumpt. C1W Vk (ML)	Water into Reservoir (ML)	Flow Rate into Reservoir (ML/day)
23	18.1250	1.3958	7.7250	1.3667	4.9300	2.7075	65.0
24	18.1250	1.1388	7.7250	1.3667	4.5538	3.3408	80.2
1	18.1250	0.8167	7.7250	1.3667	4.1371	4.0796	97.9
2	18.1250	0.8167	7.7250	1.3667	3.7879	4.4288	106.3
3	18.1250	0.8167	7.7250	1.3667	3.5983	4.6183	110.8
4	18.1250	0.8167	7.7250	1.3667	3.2758	4.9408	118.6
5	18.1250	0.8167	7.7250	1.3667	3.4263	4.7904	115.0
6	18.1250	0.8167	7.7250	1.3667	3.7142	4.5025	108.1
Total =	145.0000	7.4346	61.8000	10.9333	31.4233	33.4087	
Check:	145.0000	7.4346	61.8000	10.9333	31.4233	33.4087	

Table 5.12a - Carlington Heights Pump Schedule for a Typical Winter Day

Hour during control interval	Water Pumped XQ (ML)	Water Pumped to 2C XQ (ML)	Water Pumped to 1E XQ (ML)	Water Pumped to CH2W XQ (ML)	Water Consumpt. C1W Vk (ML)	Water from Reservoir (ML)	Flow Rate from Reservoir (ML/day)	
7	6.6042	1.4775	0.0000	1.3667	4.8763	1.1162	26.8	
8	9.8083	2.0700	3.8625	1.3667	5.7233	3.2142	77.1	
9	6.3269	2.1496	0.0000	1.3667	6.0454	3.2347	77.6	RESTRICTION
10	7.2379	2.1275	0.0000	1.3667	5.7146	1.9708	47.3	PERIOD
11	7.3299	1.5542	0.0000	1.3667	5.9192	1.5101	36.2	
12	9.8083	2.1142	3.8625	1.3667	6.0517	3.5867	86.1	
13	9.8083	2.1250	3.8625	1.3667	5.7304	3.2763	78.6	
14	9.8083	1.8463	3.8625	1.3667	5.8608	3.1279	75.1	
15	7.9787	1.8421	0.0000	1.3667	5.4667	0.6967	16.7	
16	7.2425	1.5544	0.0000	1.3667	5.5579	1.2365	29.7	RESTRICTION
17	7.9787	1.8964	0.0000	1.3667	5.0508	0.3353	8.0	PERIOD
18	8.6309	1.8923	0.0000	1.3667	5.4113	0.0393	0.9	@ WPPs
19	8.6750	2.0352	0.3925	1.3667	5.3058	0.4252	10.2	
20	9.8083	1.9977	3.8625	1.3667	5.3879	2.8064	67.4	
21	8.6750	1.7444	3.8625	1.3667	5.3246	3.6231	87.0	
22	8.6750	1.6614	3.8625	1.3667	4.9938	3.2094	77.0	
Total =	134.3964	30.0880	27.4300	21.8667	88.4204	33.4087		
Check:	134.3964	30.0880	27.4300	21.8667	88.4204	33.4087		

Table 5.12b - Carlington Heights Hourly Coefficients for a Typical Winter Day

Hour of the day	FS1W X15(BBS)	FS1W X16(BSS)	FS1W X18(BBSS)	FS1W X19(BSSS)	FS1W X20(BBSSS)	Constraints (X)<=1	Constraints FvTv <=0	
7:00	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	-1.1162	
8:00	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	-3.2142	
9:00	0.0000	0.2447	0.0000	0.7553	0.0000	1.0000	-3.2347	RESTRICTION
10:00	0.6760	0.0000	0.0000	0.3240	0.0000	1.0000	-1.9708	PERIOD
11:00	0.7741	0.0000	0.0000	0.2259	0.0000	1.0000	-1.5101	
12:00	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	-3.5867	
13:00	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	-3.2763	
14:00	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	-3.1279	
15:00	0.8072	0.0000	0.0000	0.0000	0.1928	1.0000	-0.6967	
16:00	0.0000	0.5268	0.0000	0.0876	0.3856	1.0000	-1.2365	RESTRICTION
17:00	0.8072	0.0000	0.0000	0.0000	0.1928	1.0000	-0.3353	PERIOD
18:00	0.0385	0.0000	0.9615	0.0000	0.0000	1.0000	-0.0393	@ WPPs
19:00	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	-0.4252	
20:00	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	-2.8064	
21:00	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	-3.6231	
22:00	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	-3.2094	
Total =	3.1030	0.7715	3.9615	2.3928	5.7712	F (X) =	-0.0000	
Check:	3.1030	0.7715	3.9615	2.3928	5.7712		Yes	

Table 5.13a - Glen Cairn/Stittsville Pump Schedule for a Typical Summer Night

Hour during control interval	Water Pumped BR2W XQ (ML)	Water Pumped CH2W XQ (ML)	Water Consumpt. C2W Vk (ML)	Water Consumpt. CBAR Vk (ML)	Water into both Reservoirs (ML)	Flow Rate into both Reservoirs (ML/d)
23	7.7917	0.0000	3.8513	0.3467	3.5938	86.3
24	5.1704	0.0000	3.2208	0.2458	1.7037	40.9
1	5.1704	0.0000	2.5467	0.1654	2.4583	59.0
2	5.1704	0.0000	2.2258	0.1379	2.8066	67.4
3	5.1704	0.0000	2.1204	0.1317	2.9183	70.0
4	5.1704	0.0000	2.0158	0.1283	3.0262	72.6
5	7.7917	0.0000	1.9333	0.1283	5.7300	137.5
6	7.7917	0.0000	2.2588	0.1696	5.3633	128.7
Total =	49.2268	0.0000	20.1729	1.4538	27.6001	
Check:	49.2268	0.0000	20.1729	1.4538	27.6001	

Table 5.13b - Glen Cairn/Stittsville Hourly Coefficients for a Typical Summer Night

Hour of the day	BR2W X1 (E)	BR2W X5 (EB)	Constraints Sum(X)=1	XQ-Vk>=0
23:00	0.0000	1.0000	1.0000	3.5938
24:00	0.6486	0.3514	1.0000	1.7037
1:00	0.6486	0.3514	1.0000	2.4583
2:00	0.6486	0.3514	1.0000	2.8066
3:00	0.6486	0.3514	1.0000	2.9183
4:00	0.6486	0.3514	1.0000	3.0262
5:00	0.0000	1.0000	1.0000	5.7300
6:00	0.0000	1.0000	1.0000	5.3633
Total =	3.2429	4.7571	F(X) =	0.0001
Check:	3.2429	4.7571		Yes

Table 5.14a - Glen Cairn/Stittsville Pump Schedule for a Typical Summer Day

Hour during control interval	Water Pumped BR2W XQ (ML)	Water Pumped CH2W XQ (ML)	Water Consumpt. C2W Vk (ML)	Water Consumpt. CBAR Vk (ML)	Water from both Reservoirs (ML)	Flow Rate from both Reservoirs (ML/day)
7	1.8180	1.3667	3.1825	0.3229	0.3208	7.7
8	1.8180	1.3667	3.9979	0.3854	1.1987	28.8
9	1.8180	1.3667	4.2958	0.4046	1.5158	36.4
10	1.8180	1.3667	4.7538	0.4338	2.0029	48.1
11	1.8180	1.3667	4.9775	0.4342	2.2270	53.4
12	1.8180	1.3667	4.7700	0.4204	2.0058	48.1
13	1.8180	1.3667	4.4821	0.3913	1.6887	40.5
14	1.8180	1.3667	4.4958	0.3729	1.6841	40.4
15	1.8180	1.3667	4.3908	0.3575	1.5637	37.5
16	1.8180	1.3667	4.2396	0.3604	1.4154	34.0
17	1.8180	1.3667	4.3846	0.3913	1.5912	38.2
18	1.8180	1.3667	4.5317	0.4533	1.8004	43.2
19	1.8180	1.3667	4.8696	0.4979	2.1829	52.4
20	1.8180	1.3667	4.9763	0.5333	2.3249	55.8
21	1.8180	1.3667	4.9346	0.5492	2.2991	55.2
22	1.8180	1.3667	4.4829	0.4804	1.7787	42.7
Total =	29.0874	21.8667	71.7654	6.7888	27.6001	
Check:	29.0874	21.8667	71.7654	6.7888	27.6001	

RESTRICTION PERIOD @ WPPs (hours 10–15)

Table 5.14b - Glen Cairn/Stittsville Hourly Coefficients for a Typical Summer Day

Hour of the day	BR2W X1 (E)	CH2W X10 (SS)	Constraints Sum(X)<=2	Constraints XQ-Vk<=0
7:00	0.4848	1.0000	1.4848	-0.3208
8:00	0.4848	1.0000	1.4848	-1.1987
9:00	0.4848	1.0000	1.4848	-1.5158
10:00	0.4848	1.0000	1.4848	-2.0029
11:00	0.4848	1.0000	1.4848	-2.2270
12:00	0.4848	1.0000	1.4848	-2.0058
13:00	0.4848	1.0000	1.4848	-1.6887
14:00	0.4848	1.0000	1.4848	-1.6841
15:00	0.4848	1.0000	1.4848	-1.5637
16:00	0.4848	1.0000	1.4848	-1.4154
17:00	0.4848	1.0000	1.4848	-1.5912
18:00	0.4848	1.0000	1.4848	-1.8004
19:00	0.4848	1.0000	1.4848	-2.1829
20:00	0.4848	1.0000	1.4848	-2.3249
21:00	0.4848	1.0000	1.4848	-2.2991
22:00	0.4848	1.0000	1.4848	-1.7787
Total =	7.7566	16.0000	F(X) =	0.0001
Check:	7.7566	16.0000		Yes

RESTRICTION PERIOD @ WPPs

Table 5.15a - Glen Cairn/Stittsville Pump Schedule for a Typical Winter Night

Hour during control interval	Water Pumped BR2W XQ (ML)	Water Pumped CH2W XQ (ML)	Water Consumpt. C2W Vk (ML)	Water Consumpt. CBAR Vk (ML)	Water into both Reservoirs (ML)	Flow Rate into both Reservoirs (ML/d)
23	3.7500	1.3667	2.9138	0.2613	1.9417	46.6
24	3.7500	1.3667	2.6367	0.2158	2.2642	54.3
1	3.7500	1.3667	1.9067	0.1517	3.0583	73.4
2	3.7500	1.3667	1.6979	0.1338	3.2850	78.8
3	3.7500	1.3667	1.6500	0.1271	3.3396	80.1
4	3.7500	1.3667	1.6138	0.1279	3.3750	81.0
5	3.7500	1.3667	1.5125	0.1267	3.4775	83.5
6	7.3770	1.3667	2.0158	0.1692	6.5587	157.4
Total =	33.6271	10.9333	15.9471	1.3133	27.3000	
Check:	33.6271	10.9333	15.9471	1.3133	27.3000	

Table 5.15b - Glen Cairn/Stittsville Hourly Coefficients for a Typical Winter Night

Hour of the day	BR2W X1 (E)	BR2W X5 (EB)	CH2W X10 (SS)	Constraints 1<=X<=2	XQ-Vk>=0
23:00	1.0000	0.0000	1.0000	2.0000	1.9417
24:00	1.0000	0.0000	1.0000	2.0000	2.2642
1:00	1.0000	0.0000	1.0000	2.0000	3.0583
2:00	1.0000	0.0000	1.0000	2.0000	3.2850
3:00	1.0000	0.0000	1.0000	2.0000	3.3396
4:00	1.0000	0.0000	1.0000	2.0000	3.3750
5:00	1.0000	0.0000	1.0000	2.0000	3.4775
6:00	0.1026	0.8974	1.0000	2.0000	6.5587
Total =	7.1026	0.8974	8.0000	F(X) =	-0.0001
Check:	7.1026	0.8974	8.0000		Yes

Table 5.16a - Glen Cairn/Stittsville Pump Schedule for a Typical Winter Day

Hour during control interval	Water Pumped BR2W XQ (ML)	Water Pumped CH2W XQ (ML)	Water Consumpt. C2W Vk (ML)	Water Consumpt. CBAR Vk (ML)	Water from both Reservoirs (ML)	Flow Rate from both Reservoirs (ML/day)	
7	0.5796	1.3667	3.1238	0.3504	1.5279	36.7	
8	0.8869	1.3667	3.7738	0.4025	1.9227	46.1	
9	0.0000	1.3667	3.8571	0.3308	2.8213	67.7	RESTRICTION
10	0.0000	1.3667	3.9308	0.3429	2.9071	69.8	PERIOD
11	0.8869	1.3667	3.9579	0.3467	2.0510	49.2	
12	0.8869	1.3667	3.7888	0.3375	1.8727	44.9	
13	0.8869	1.3667	3.5325	0.3258	1.6047	38.5	
14	0.8869	1.3667	3.4592	0.2908	1.4964	35.9	
15	0.8869	1.3667	3.2058	0.2758	1.2281	29.5	
16	0.8869	1.3667	3.2804	0.2771	1.3039	31.3	RESTRICTION
17	0.8869	1.3667	3.1783	0.2975	1.2222	29.3	PERIOD
18	0.8869	1.3667	3.4633	0.3313	1.5410	37.0	@ WPPs
19	0.8869	1.3667	3.6542	0.3721	1.7727	42.5	
20	0.8869	1.3667	3.4329	0.3683	1.5477	37.1	
21	0.8869	1.3667	3.2888	0.3300	1.3652	32.8	
22	0.8869	1.3667	3.0742	0.2950	1.1156	26.8	
Total =	12.1096	21.8667	56.0017	5.2746	27.3000		
Check:	12.1096	21.8667	56.0017	5.2746	27.3000		

Table 5.16b - Glen Cairn/Stittsville Hourly Coefficients for a Typical Winter Day

Hour of the day	BR2W X1 (E)	CH2W X10 (SS)	Constraints Sum(X)<=2	XQ-Vk<=0	
7:00	0.1546	1.0000	1.1546	-1.5279	
8:00	0.2365	1.0000	1.2365	-1.9227	
9:00	0.0000	1.0000	1.0000	-2.8213	RESTRICTION
10:00	0.0000	1.0000	1.0000	-2.9071	PERIOD
11:00	0.2365	1.0000	1.2365	-2.0510	
12:00	0.2365	1.0000	1.2365	-1.8727	
13:00	0.2365	1.0000	1.2365	-1.6047	
14:00	0.2365	1.0000	1.2365	-1.4964	
15:00	0.2365	1.0000	1.2365	-1.2281	
16:00	0.2365	1.0000	1.2365	-1.3039	RESTRICTION
17:00	0.2365	1.0000	1.2365	-1.2222	PERIOD
18:00	0.2365	1.0000	1.2365	-1.5410	@ WPPs
19:00	0.2365	1.0000	1.2365	-1.7727	
20:00	0.2365	1.0000	1.2365	-1.5477	
21:00	0.2365	1.0000	1.2365	-1.3652	
22:00	0.2365	1.0000	1.2365	-1.1156	
Total =	3.2292	16.0000	F(X) =	-0.0000	
Check:	3.2292	16.0000		Yes	

Table 5.17 - Barrhaven Pump Schedule for a Typical Summer Night

Hour during control interval	Pumps Required	Water Pumped XQ (ML)	Water Consumpt. Vk (ML)	Portion of an hour
1	S	0.1875	0.1654	0.8822
2	S	0.1875	0.1379	0.7356
3	S	0.1875	0.1317	0.7022
4	S	0.1875	0.1283	0.6844
5	S	0.1875	0.1283	0.6844
6	S	0.1875	0.1696	0.9044
	Total =	1.1250	0.8613	4.5933
	Check:	1.1250	0.8613	(6.0000)

Table 5.18a - Barrhaven Pump Schedule for a Typical Summer Day

Hour during control interval	Pumps Required	Water Pumped XQ (ML)	Water Consumpt. Vk (ML)	
7	BS then S	0.3229	0.3229	
8	BS then S	0.3854	0.3854	
9	BS then S	0.4046	0.4046	
10	BS then S	0.4338	0.4338	
11	BS then S	0.4342	0.4342	
12	BS then S	0.4204	0.4204	RESTRICTION
13	BS then S	0.3913	0.3913	PERIOD
14	BS then S	0.3729	0.3729	@ WPPs
15	BS then S	0.3575	0.3575	
16	BS then S	0.3604	0.3604	
17	BS then S	0.3913	0.3913	
18	BS then S	0.4533	0.4533	
19	BS then S	0.4979	0.4979	
20	BS then S	0.5333	0.5333	
21	BS then S	0.5492	0.5492	
22	BS then S	0.4804	0.4804	
23	BS then S	0.3468	0.3467	
24	BS then S	0.2458	0.2458	
	Total =	7.3813	7.3813	
	Check:	7.3813	7.3813	

Table 5.18b - Barrhaven Hourly Coefficients for a Typical Summer Day

Hour of the day	X8 (BS)	X4 (S)	Constraints Sum(X)=1	XQ-Vk=0	
7:00	0.0939	0.9061	1.0000	0.0000	
8:00	0.1373	0.8627	1.0000	0.0000	
9:00	0.1506	0.8494	1.0000	0.0000	
10:00	0.1708	0.8292	1.0000	-0.0000	
11:00	0.1711	0.8289	1.0000	-0.0000	
12:00	0.1616	0.8384	1.0000	-0.0000	RESTRICTION
13:00	0.1413	0.8587	1.0000	-0.0000	PERIOD
14:00	0.1286	0.8714	1.0000	0.0000	@ WPPs
15:00	0.1179	0.8821	1.0000	-0.0000	
16:00	0.1199	0.8801	1.0000	-0.0000	
17:00	0.1413	0.8587	1.0000	-0.0000	
18:00	0.1844	0.8156	1.0000	-0.0000	
19:00	0.2153	0.7847	1.0000	-0.0000	
20:00	0.2399	0.7601	1.0000	-0.0000	
21:00	0.2509	0.7491	1.0000	0.0000	
22:00	0.2032	0.7968	1.0000	-0.0000	
23:00	0.1104	0.8896	1.0000	0.0000	
24:00	0.0405	0.9595	1.0000	0.0000	
Total =	2.7790	15.2211	F(X) =	0.0000	
Check:	2.7790	15.2211		Yes	

Table 5.19 - Barrhaven Pump Schedule for a Typical Winter Night

Hour during control interval	Pumps Required	Water Pumped XQ (ML)	Water Consumpt. Vk (ML)	Portion of an hour
1	S	0.1875	0.1517	0.8089
2	S	0.1875	0.1338	0.7133
3	S	0.1875	0.1271	0.6778
4	S	0.1875	0.1279	0.6822
5	S	0.1875	0.1267	0.6756
6	S	0.1875	0.1692	0.9022
	Total =	1.1250	0.8363	4.4600
	Check:	1.1250	0.8363	(6.0000)

Table 5.20a - Barrhaven Pump Schedule for a Typical Winter Day

Hour during control interval	Pumps Required	Water Pumped XQ (ML)	Water Consumpt. Vk (ML)	
7	BS then S	0.3504	0.3504	
8	BS then S	0.4025	0.4025	
9	BS then S	0.3308	0.3308	RESTRICTION
10	BS then S	0.3429	0.3429	PERIOD
11	BS then S	0.3467	0.3467	
12	BS then S	0.3467	0.3375	
13	BS then S	0.3258	0.3258	
14	BS then S	0.2908	0.2908	
15	BS then S	0.2758	0.2758	
16	BS then S	0.2771	0.2771	RESTRICTION
17	BS then S	0.2975	0.2975	PERIOD
18	BS then S	0.3313	0.3313	@ WPPs
19	BS then S	0.3721	0.3721	
20	BS then S	0.3592	0.3683	
21	BS then S	0.3300	0.3300	
22	BS then S	0.2950	0.2950	
23	BS then S	0.2613	0.2613	
24	BS then S	0.2158	0.2158	
	Total =	5.7517	5.7517	
	Check:	5.7517	5.7517	

Table 5.20b - Barrhaven Hourly Coefficients for a Typical Winter Day

Hour of the day	X8 (BS)	X4 (S)	Constraints Sum(X)=1	XQ-Vk=0	
7:00	0.1130	0.8870	1.0000	-0.0000	
8:00	0.1491	0.8509	1.0000	-0.0000	
9:00	0.0994	0.9005	1.0000	0.0000	RESTRICTION
10:00	0.1078	0.8922	1.0000	-0.0000	PERIOD
11:00	0.1104	0.8896	1.0000	-0.0000	
12:00	0.1104	0.8896	1.0000	-0.0000	
13:00	0.0959	0.9041	1.0000	0.0000	
14:00	0.0717	0.9283	1.0000	0.0000	
15:00	0.0613	0.9387	1.0000	0.0000	
16:00	0.0621	0.9379	1.0000	0.0000	RESTRICTION
17:00	0.0762	0.9238	1.0000	0.0000	PERIOD
18:00	0.0996	0.9004	1.0000	0.0000	@ WPPs
19:00	0.1280	0.8720	1.0000	0.0000	
20:00	0.1191	0.8809	1.0000	0.0000	
21:00	0.0987	0.9013	1.0000	0.0000	
22:00	0.0745	0.9255	1.0000	0.0000	
23:00	0.0510	0.9490	1.0000	0.0000	
24:00	0.0202	0.9798	1.0000	0.0000	
Total =	1.6485	16.3516	F(X) =	0.0000	
Check:	1.6485	16.3516		Yes	

Table 5.21a - Britannia WPP Summer Energy Costs

BRITANNIA		Night	Day	Total	$/ML	Britannia
BR1W	$	$269.74	$378.50	$648.24		**Total ML =**
(Pumping +	kW.h	17072	7963	25035		157.40
Treatment)	ML	53.00	26.08	79.08	8.20	**% of RMOC**
BR2W	$	$273.61	$481.89	$755.50		38.7%
(Pumping +	kW.h	17317	10138	27455		**Total kW.h =**
Treatment)	ML	49.23	29.09	78.31	9.65	58749.14
Base Load	$	$32.96	$198.34	$231.30		**Total $/ML =**
(Heating + ...)	kW.h	2086	4173	6259		10.39
Base Load =	6259.00	kW.h/d	**Daily Total:**	**$1,635.05**	**Bill:**	**Difference:**
			Monthly:	**$50,897.34**	**$56,707.45**	**10.25%**

Table 5.21b - Lemieux Island WPP Summer Energy Costs

LEMIEUX ISLAND		Night	Day	Total	$/ML	Lemieux Is.
LI1W +	$	$249.51	$0.00	$249.51		**Total ML =**
FS1W	kW.h	15792	0	15792		248.93
(P + T)	ML	92.00	0.00	92.00	2.71	**% of RMOC**
FS1W	$	$0.00	$820.55	$820.55		61.3%
(Pumping +	kW.h	0	17263	17263		**Total kW.h =**
Treatment)	ML	0.00	156.93	156.93	5.23	40876.67
Base Load	$	$41.20	$247.87	$289.07		**Total $/ML =**
(Heating + ...)	kW.h	2607	5215	7822		5.46
Base Ld (LI)=	6504.00	kW.h/d	**Daily Total:**	**$1,359.13**	**Bill:**	**Difference:**
Base Ld (FS)=	1318.00	kW.h/d	**Monthly:**	**$42,343.99**	**$32,245.35**	**-31.32%**

Table 5.21c - Compilation of WPPs' Summer Energy Costs

SUMMARY	Monthly $	Bill $	Difference $	Savings %
BRITANNIA	$50,897.34	$56,707.45	$5,810.11	10.25%
LEMIEUX	$42,343.99	$32,245.35	($10,098.65)	-31.32%
TOTAL =	$93,241.33	$88,952.79	($4,288.54)	**-4.82%**

Table 5.22a - Hurdman Bridge Summer Energy Costs

HURDMAN BRIDGE		Night	Day	Total	$/ML
HB1E	$	$326.77	$271.76	$598.53	
	kW.h	5814	4836	10650	
	ML	60.21	50.07	110.28	5.43
Base Load	$	$48.41	$96.81	$145.22	(+ base load)
	kW.h	861	1723	2584	6.74
*Base Load =	2584.00	kW.h/d	**Daily Total:**	**$743.76**	
	(120*ML)-kW.h		**Monthly:**	**$23,311.13**	

Table 5.22b - Billings Bridge Summer Energy Costs

BILLINGS BRIDGE		Night*	Day*	Total	$/ML
BB2C	$	$69.26	$364.42	$433.68	
	kW.h	1232	6484	7717	
	ML	8.44	44.99	53.43	8.12
Base Load	$	$31.96	$95.88	$127.84	(+ base load)
	kW.h	569	1706	2275	10.51
Base Load =	2274.68	kW.h/d	**Daily Total:**	**$561.52**	
	(187*ML)-kW.h		**Monthly:**	**$17,661.87**	

Table 5.22c - Carlington Heights 2W Summer Energy Costs

CARLINGTON HGTS 2W		Night	Day	Total	$/ML
CH2W	$	$0.00	$167.25	$167.25	
	kW.h	0	2976	2976	
	ML	0.00	21.87	21.87	7.65
Base Load	$	$22.49	$44.98	$67.47	(+ base load)
	kW.h	400	800	1201	10.73
Base Load =	1200.53	kW.h/d	**Daily Total:**	**$234.72**	
	(191*ML)-kW.h		**Monthly:**	**$7,531.06**	

Table 5.22d - Barrhaven Summer Energy Costs

BARRHAVEN		Night*	Day*	Total	$/ML
BHPS	$	$9.97	$70.10	$80.07	
	kW.h	180	1265	1445	
	ML	1.13	7.38	8.51	9.41
Base Load	$	$2.25	$6.75	$9.00	(+ base load)
	kW.h	41	122	162	10.47
Base Load =	162.39	kW.h/d	**Daily Total:**	**$89.07**	
	(189*ML)-kW.h		**Monthly:**	**$3,011.58**	

Table 5.23a - Britannia WPP Winter Energy Costs

BRITANNIA		Night	Day	Total	$/ML	Britannia
BR1W	$	$392.66	$0.00	$392.66		**Total ML =**
(Pumping +	kW.h	17072	0	17072		98.74
Treatment)	ML	53.00	0.00	53.00	7.41	**% of RMOC**
BR2W	$	$270.26	$242.82	$513.08		30.4%
(Pumping +	kW.h	11750	4221	15971		**Total kW.h =**
Treatment)	ML	33.63	12.11	45.74	11.22	39301.98
Base Load	$	$32.96	$198.34	$231.30		**Total $/ML =**
(Heating + ...)	kW.h	2086	4173	6259		11.52
Base Load =	6259.00	kW.h/d	**Daily Total:**	**$1,137.04**	**Bill:**	**Difference:**
			Monthly:	**$35,518.69**	**$53,606.75**	**33.74%**

Table 5.23b - Lemieux Island WPP Winter Energy Costs

LEMIEUX ISLAND		Night	Day	Total	$/ML	Lemieux Is.
LI1W +	$	$363.22	$0.00	$363.22		**Total ML =**
FS1W	kW.h	15792	0	15792		226.40
(P + T)	ML	92.00	0.00	92.00	3.95	**% of RMOC**
FS1W	$	$0.00	$850.55	$850.55		69.6%
(Pumping +	kW.h	0	0	0		**Total kW.h =**
Treatment)	ML	0.00	134.40	134.40	6.33	23614.00
Base Load	$	$41.20	$247.87	$289.07		**Total $/ML =**
(Heating + ...)	kW.h	2607	5215	7822		6.64
Base Ld (LI)=	6504.00	kW.h/d	**Daily Total:**	**$1,502.83**	**Bill:**	**Difference:**
Base Ld (FS)=	1318.00	kW.h/d	**Monthly:**	**$46,858.11**	**$29,957.87**	**-56.41%**

Table 5.23c - Compilation of WPPs' Winter Energy Costs

SUMMARY	Monthly $	Bill $	Difference $	Savings %
BRITANNIA	$35,518.69	$53,606.75	$18,088.06	33.74%
LEMIEUX	$46,858.11	$29,957.87	($16,900.24)	-56.41%
TOTAL =	$82,376.80	$83,564.61	$1,187.81	**1.42%**

Table 5.24a - Hurdman Bridge Winter Energy Costs

HURDMAN BRIDGE		Night	Day	Total	$/ML
HB1E	$	$335.40	$148.87	$484.27	
	kW.h	5968	2649	8617	
	ML	61.80	27.43	89.23	5.43
Base Load	$	$39.17	$78.33	$117.50	(+ base load)
	kW.h	697	1394	2091	6.74
*Base Load =	2090.70	kW.h/d	**Daily Total:**	**$601.77**	
	(120*ML)-kW.h		**Monthly:**	**$18,909.48**	

Table 5.24b - Billings Bridge Winter Energy Costs

BILLINGS BRIDGE		Night*	Day*	Total	$/ML
BB2C	$	$44.17	$264.24	$308.42	
	kW.h	786	4702	5488	
	ML	4.90	32.62	37.52	8.22
Base Load	$	$21.48	$64.44	$85.92	(+ base load)
	kW.h	382	1147	1529	10.51
Base Load =	1528.87	kW.h/d	**Daily Total:**	**$394.34**	
	(187*ML)-kW.h		**Monthly:**	**$12,479.21**	

Table 5.24c - Carlington Heights 2W Winter Energy Costs

CARLINGTON HGTS 2W		Night	Day	Total	$/ML
CH2W	$	$83.63	$167.25	$250.88	
	kW.h	1488	2976	4464	
	ML	10.93	21.87	32.80	7.65
Base Load	$	$33.73	$67.47	$101.20	(+ base load)
	kW.h	600	1201	1801	10.73
Base Load =	1800.80	kW.h/d	**Daily Total:**	**$352.08**	
	(191*ML)-kW.h		**Monthly:**	**$11,169.23**	

Table 5.24d - Barrhaven Winter Energy Costs

BARRHAVEN		Night*	Day*	Total	$/ML
BHPS	$	$9.97	$53.75	$63.73	
	kW.h	180	970	1150	
	ML	1.13	5.75	6.88	9.27
Base Load	$	$2.07	$6.21	$8.28	(+ base load)
	kW.h	37	112	149	10.47
Base Load =	149.42	kW.h/d	**Daily Total:**	**$72.00**	
	(189*ML)-kW.h		**Monthly:**	**$2,482.61**	

Table 5.25a - Britannia WPP Summer Energy Costs (LI WPP Utrt = 80 kW.h/ML)

BRITANNIA		Night	Day	Total	$/ML	Britannia
BR1W	$	$269.74	$378.50	$648.24		**Total ML =**
(Pumping +	kW.h	17072	7963	25035		157.40
Treatment)	ML	53.00	26.08	79.08	8.20	**% of RMOC**
BR2W	$	$273.61	$481.89	$755.50		38.7%
(Pumping +	kW.h	17317	10138	27455		**Total kW.h =**
Treatment)	ML	49.23	29.09	78.31	9.65	58749.14
Base Load	$	$32.96	$198.34	$231.30		**Total $/ML =**
(Heating + ...)	kW.h	2086	4173	6259		10.39
Base Load =	6259.00	kW.h/d	**Daily Total:**	**$1,635.05**	**Bill:**	**Difference:**
			Monthly:	**$50,897.34**	**$56,707.45**	**10.25%**

Table 5.25b - Lemieux Island WPP Summer Energy Costs (LI WPP Utrt = 80 kW.h/ML)

LEMIEUX ISLAND		Night	Day	Total	$/ML	Lemieux Is.
LI1W +	$	$205.91	$0.00	$205.91		**Total ML =**
FS1W	kW.h	13032	0	13032		248.93
(P + T)	ML	92.00	0.00	92.00	2.24	**% of RMOC**
FS1W	$	$0.00	$596.77	$596.77		61.3%
(Pumping +	kW.h	0	12555	12555		**Total kW.h =**
Treatment)	ML	0.00	156.93	156.93	3.80	33408.67
Base Load	$	$41.20	$247.87	$289.07		**Total $/ML =**
(Heating + ...)	kW.h	2607	5215	7822		4.39
Base Ld (LI)=	6504.00	kW.h/d	**Daily Total:**	**$1,091.74**	**Bill:**	**Difference:**
Base Ld (FS)=	1318.00	kW.h/d	**Monthly:**	**$34,054.75**	**$32,245.35**	**-5.61%**

Table 5.25c - Compilation of WPPs' Summer Energy Costs (LI WPP Utrt = 80 kW.h/ML)

SUMMARY	Monthly $	Bill $	Difference $	Savings %
BRITANNIA	$50,897.34	$56,707.45	$5,810.11	10.25%
LEMIEUX	$34,054.75	$32,245.35	($1,809.40)	-5.61%
TOTAL =	$84,952.09	$88,952.79	$4,000.70	4.50%

Table 5.26a - Britannia WPP Winter Energy Costs (LI WPP Utrt = 80 kW.h/ML)

BRITANNIA		Night	Day	Total	$/ML	Britannia
BR1W	$	$392.66	$0.00	$392.66		**Total ML =**
(Pumping +	kW.h	17072	0	17072		98.74
Treatment)	ML	53.00	0.00	53.00	7.41	**% of RMOC**
BR2W	$	$270.26	$242.82	$513.08		30.4%
(Pumping +	kW.h	11750	4221	15971		**Total kW.h =**
Treatment)	ML	33.63	12.11	45.74	11.22	39301.98
Base Load	$	$32.96	$198.34	$231.30		**Total $/ML =**
(Heating + ...)	kW.h	2086	4173	6259		11.52
Base Load =	6259.00	kW.h/d	**Daily Total:**	**$1,137.04**	**Bill:**	**Difference:**
			Monthly:	**$35,518.69**	**$53,606.75**	**33.74%**

Table 5.26b - Lemieux Island WPP Winter Energy Costs (LI WPP Utrt = 80 kW.h/ML)

LEMIEUX ISLAND		Night	Day	Total	$/ML	Lemieux Is.
LI1W +	$	$299.74	$0.00	$299.74		**Total ML =**
FS1W	kW.h	13032	0	13032		226.40
(P + T)	ML	92.00	0.00	92.00	3.26	**% of RMOC**
FS1W	$	$0.00	$618.58	$618.58		69.6%
(Pumping +	kW.h	0	0	0		**Total kW.h =**
Treatment)	ML	0.00	134.40	134.40	4.60	20854.00
Base Load	$	$41.20	$247.87	$289.07		**Total $/ML =**
(Heating + ...)	kW.h	2607	5215	7822		5.33
Base Ld (LI)=	6504.00	kW.h/d	**Daily Total:**	**$1,207.38**	**Bill:**	**Difference:**
Base Ld (FS)=	1318.00	kW.h/d	**Monthly:**	**$37,699.22**	**$29,957.87**	**-25.84%**

Table 5.26c - Compilation of WPPs' Winter Energy Costs (LI WPP Utrt = 80 kW.h/ML)

SUMMARY	Monthly $	Bill $	Difference $	Savings %
BRITANNIA	$35,518.69	$53,606.75	$18,088.06	33.74%
LEMIEUX	$37,699.22	$29,957.87	($7,741.35)	-25.84%
TOTAL =	$73,217.91	$83,564.61	$10,346.71	12.38%

Table 5.27a - Britannia WPP Summer Energy Costs (LI WPP Utrt = 75 kW.h/ML)

BRITANNIA		Night	Day	Total	$/ML	Britannia
BR1W	$	$269.74	$378.50	$648.24		**Total ML =**
(Pumping +	kW.h	17072	7963	25035		157.40
Treatment)	ML	53.00	26.08	79.08	8.20	**% of RMOC**
BR2W	$	$273.61	$481.89	$755.50		38.7%
(Pumping +	kW.h	17317	10138	27455		**Total kW.h =**
Treatment)	ML	49.23	29.09	78.31	9.65	58749.14
Base Load	$	$32.96	$198.34	$231.30		**Total $/ML =**
(Heating + ...)	kW.h	2086	4173	6259		10.39
Base Load =	6259.00	kW.h/d	**Daily Total:**	**$1,635.05**	**Bill:**	**Difference:**
			Monthly:	**$50,897.34**	**$56,707.45**	**10.25%**

Table 5.27b - Lemieux Island WPP Summer Energy Costs (LI WPP Utrt = 75 kW.h/ML)

LEMIEUX ISLAND		Night	Day	Total	$/ML	Lemieux Is.
LI1W +	$	$198.64	$0.00	$198.64		**Total ML =**
FS1W	kW.h	12572	0	12572		248.93
(P + T)	ML	92.00	0.00	92.00	2.16	**% of RMOC**
FS1W	$	$0.00	$559.47	$559.47		61.3%
(Pumping +	kW.h	0	11770	11770		**Total kW.h =**
Treatment)	ML	0.00	156.93	156.93	3.57	32164.00
Base Load	$	$41.20	$247.87	$289.07		**Total $/ML =**
(Heating + ...)	kW.h	2607	5215	7822		4.21
Base Ld (LI)=	6504.00	kW.h/d	**Daily Total:**	**$1,047.17**	**Bill:**	**Difference:**
Base Ld (FS)=	1318.00	kW.h/d	**Monthly:**	**$32,673.21**	**$32,245.35**	**-1.33%**

Table 5.27c - Compilation of WPPs' Summer Energy Costs (LI WPP Utrt = 75 kW.h/ML)

SUMMARY	Monthly $	Bill $	Difference $	Savings %
BRITANNIA	$50,897.34	$56,707.45	$5,810.11	10.25%
LEMIEUX	$32,673.21	$32,245.35	($427.86)	-1.33%
TOTAL =	$83,570.55	$88,952.79	$5,382.24	6.05%

Table 5.28a - Britannia WPP Winter Energy Costs (LI WPP Utrt = 75 kW.h/ML)

BRITANNIA		Night	Day	Total	$/ML	Britannia
BR1W	$	$392.66	$0.00	$392.66		**Total ML =**
(Pumping +	kW.h	17072	0	17072		98.74
Treatment)	ML	53.00	0.00	53.00	7.41	**% of RMOC**
BR2W	$	$270.26	$242.82	$513.08		30.4%
(Pumping +	kW.h	11750	4221	15971		**Total kW.h =**
Treatment)	ML	33.63	12.11	45.74	11.22	39301.98
Base Load	$	$32.96	$198.34	$231.30		**Total $/ML =**
(Heating + ...)	kW.h	2086	4173	6259		11.52
Base Load =	6259.00	kW.h/d	**Daily Total:**	**$1,137.04**	**Bill:**	**Difference:**
			Monthly:	**$35,518.69**	**$53,606.75**	**33.74%**

Table 5.28b - Lemieux Island WPP Winter Energy Costs (LI WPP Utrt = 75 kW.h/ML)

LEMIEUX ISLAND		Night	Day	Total	$/ML	Lemieux Is.
LI1W +	$	$289.16	$0.00	$289.16		**Total ML =**
FS1W	kW.h	12572	0	12572		226.40
(P + T)	ML	92.00	0.00	92.00	3.14	**% of RMOC**
FS1W	$	$0.00	$579.92	$579.92		69.6%
(Pumping +	kW.h	0	0	0		**Total kW.h =**
Treatment)	ML	0.00	134.40	134.40	4.32	20394.00
Base Load	$	$41.20	$247.87	$289.07		**Total $/ML =**
(Heating + ...)	kW.h	2607	5215	7822		5.12
Base Ld (LI)=	6504.00	kW.h/d	**Daily Total:**	**$1,158.14**	**Bill:**	**Difference:**
Base Ld (FS)=	1318.00	kW.h/d	**Monthly:**	**$36,172.74**	**$29,957.87**	**-20.75%**

Table 5.28c - Compilation of WPPs' Winter Energy Costs (LI WPP Utrt = 75 kW.h/ML)

SUMMARY	Monthly $	Bill $	Difference $	Savings %
BRITANNIA	$35,518.69	$53,606.75	$18,088.06	33.74%
LEMIEUX	$36,172.74	$29,957.87	($6,214.87)	-20.75%
TOTAL =	$71,691.43	$83,564.61	$11,873.19	14.21%

Table 5.29a - Britannia WPP Summer Energy Costs with CH2W Offline

BRITANNIA		Night	Day	Total	$/ML	Britannia
BR1W	$	$269.74	$61.19	$330.93		**Total ML =**
(Pumping +	kW.h	17072	1287	18359		157.40
Treatment)	ML	53.00	4.22	57.22	5.78	**% of RMOC**
BR2W	$	$273.61	$844.16	$1,117.77		38.7%
(Pumping +	kW.h	17317	17759	35077		**Total kW.h =**
Treatment)	ML	49.23	50.95	100.18	11.16	59694.84
Base Load	$	$32.96	$198.34	$231.30		**Total $/ML =**
(Heating + ...)	kW.h	2086	4173	6259		10.67
Base Load =	6259.00	kW.h/d	**Daily Total:**	**$1,680.00**	**Bill:**	**Difference:**
			Monthly:	**$52,290.93**	**$56,707.45**	**7.79%**

Table 5.29b - Lemieux Island WPP Summer Energy Costs with CH2W Offline

LEMIEUX ISLAND		Night	Day	Total	$/ML	Lemieux Is.
LI1W +	$	$249.51	$0.00	$249.51		**Total ML =**
FS1W	kW.h	15792	0	15792		248.93
(P + T)	ML	92.00	0.00	92.00	2.71	**% of RMOC**
FS1W	$	$0.00	$820.55	$820.55		61.3%
(Pumping +	kW.h	0	17263	17263		**Total kW.h =**
Treatment)	ML	0.00	156.93	156.93	5.23	40876.67
Base Load	$	$41.20	$247.87	$289.07		**Total $/ML =**
(Heating + ...)	kW.h	2607	5215	7822		5.46
Base Ld (LI)=	6504.00	kW.h/d	**Daily Total:**	**$1,359.13**	**Bill:**	**Difference:**
Base Ld (FS)=	1318.00	kW.h/d	**Monthly:**	**$42,343.99**	**$32,245.35**	**-31.32%**

Table 5.29c - Compilation of WPPs' Summer Energy Costs with CH2W Offline

SUMMARY	Monthly $	Bill $	Difference $	Savings %
BRITANNIA	$52,290.93	$56,707.45	$4,416.51	7.79%
LEMIEUX	$42,343.99	$32,245.35	($10,098.65)	-31.32%
TOTAL =	$94,634.93	$88,952.79	($5,682.13)	**-6.39%**

Table 5.30a - Britannia WPP Winter Energy Costs with CH2W Offline

BRITANNIA		Night	Day	Total	$/ML	Britannia
BR1W	$	$392.66	$0.00	$392.66		**Total ML =**
(Pumping +	kW.h	17072	0	17072		131.54
Treatment)	ML	53.00	0.00	53.00	7.41	**% of RMOC**
BR2W	$	$360.00	$681.30	$1,041.30		40.5%
(Pumping +	kW.h	15652	11842	27494		**Total kW.h =**
Treatment)	ML	44.56	33.98	78.54	13.26	50825.04
Base Load	$	$32.96	$198.34	$231.30		**Total $/ML =**
(Heating + ...)	kW.h	2086	4173	6259		12.66
Base Load =	6259.00	kW.h/d	**Daily Total:**	**$1,665.26**	**Bill:**	**Difference:**
			Monthly:	**$51,893.49**	**$53,606.75**	**3.20%**

Table 5.30b - Lemieux Island WPP Winter Energy Costs with CH2W Offline

LEMIEUX ISLAND		Night	Day	Total	$/ML	Lemieux Is.
LI1W +	$	$262.78	$0.00	$262.78		**Total ML =**
FS1W	kW.h	11425	0	11425		193.60
(P + T)	ML	66.56	0.00	66.56	3.95	**% of RMOC**
FS1W	$	$54.89	$666.65	$721.54		59.5%
(Pumping +	kW.h	2387	0	2387		**Total kW.h =**
Treatment)	ML	21.70	105.34	127.03	5.68	21634.03
Base Load	$	$41.20	$247.87	$289.07		**Total $/ML =**
(Heating + ...)	kW.h	2607	5215	7822		6.58
Base Ld (LI)=	6504.00	kW.h/d	**Daily Total:**	**$1,273.39**	**Bill:**	**Difference:**
Base Ld (FS)=	1318.00	kW.h/d	**Monthly:**	**$39,745.55**	**$29,957.87**	**-32.67%**

Table 5.30c - Compilation of WPPs' Winter Energy Costs with CH2W Offline

SUMMARY	Monthly $	Bill $	Difference $	Savings %
BRITANNIA	$51,893.49	$53,606.75	$1,713.26	3.20%
LEMIEUX	$39,745.55	$29,957.87	($9,787.68)	-32.67%
TOTAL =	$91,639.04	$83,564.61	($8,074.43)	-9.66%

Table 5.31 - Maximum Operating Volume of Reservoir R2W with Increasing Demand and CH2W Offline

Increase	Max Pumping @ 2W			8 hours				Maximum
in Demand	BR2W	CH2W	Total Q	Night XQ	Vk (2W)	Vk (Barh)	FvTv (Barh	FvTv (R2W)
0.0%	9.6667	0.0000	9.6667	77.3333	20.1729	1.4538	12.7000	43.0066
2.5%	9.6667	0.0000	9.6667	77.3333	20.6772	1.4901	12.7000	42.4660
5.0%	9.6667	0.0000	9.6667	77.3333	21.1815	1.5265	12.7000	41.9253
7.5%	9.6667	0.0000	9.6667	77.3333	21.6859	1.5628	12.7000	41.3846
10.0%	9.6667	0.0000	9.6667	77.3333	22.1902	1.5992	12.7000	40.8440
12.5%	9.6667	0.0000	9.6667	77.3333	22.6945	1.6355	12.7000	40.3033
15.0%	9.6667	0.0000	9.6667	77.3333	23.1988	1.6719	12.7000	39.7626
20.0%	9.6667	0.0000	9.6667	77.3333	24.2075	1.7446	12.7000	38.6813
30.0%	9.6667	0.0000	9.6667	77.3333	26.2248	1.8899	12.7000	36.5186
50.0%	9.6667	0.0000	9.6667	77.3333	30.2594	2.1807	12.7000	32.1933
60.0%	9.6667	0.0000	9.6667	77.3333	32.2766	2.3261	12.7000	30.0306
70.0%	9.6667	0.0000	9.6667	77.3333	34.2939	2.4715	12.7000	27.8679
80.0%	9.6667	0.0000	9.6667	77.3333	36.3112	2.6168	12.7000	25.7053
90.0%	9.6667	0.0000	9.6667	77.3333	38.3285	2.7622	12.7000	23.5426
100.0%	9.6667	0.0000	9.6667	77.3333	40.3458	2.9076	12.7000	21.3799

Table 5.32 - Maximum Operating Volume of Reservoir R2W with Increasing Demand and CH2W Online

Increase	Max Pumping @ 2W			8 hours				Maximum
in Demand	BR2W	CH2W	Total Q	Night XQ	Vk (2W)	Vk (Barh)	FvTv (Barh	FvTv (R2W)
0.0%	9.6667	1.3667	11.0333	88.2667	20.1729	1.4538	12.7000	53.9400
2.5%	9.6667	1.3667	11.0333	88.2667	20.6772	1.4901	12.7000	53.3993
5.0%	9.6667	1.3667	11.0333	88.2667	21.1815	1.5265	12.7000	52.8586
7.5%	9.6667	1.3667	11.0333	88.2667	21.6859	1.5628	12.7000	52.3180
10.0%	9.6667	1.3667	11.0333	88.2667	22.1902	1.5992	12.7000	51.7773
12.5%	9.6667	1.3667	11.0333	88.2667	22.6945	1.6355	12.7000	51.2366
15.0%	9.6667	1.3667	11.0333	88.2667	23.1988	1.6719	12.7000	50.6960
20.0%	9.6667	1.3667	11.0333	88.2667	24.2075	1.7446	12.7000	49.6146
30.0%	9.6667	1.3667	11.0333	88.2667	26.2248	1.8899	12.7000	47.4520
50.0%	9.6667	1.3667	11.0333	88.2667	30.2594	2.1807	12.7000	43.1266
60.0%	9.6667	1.3667	11.0333	88.2667	32.2766	2.3261	12.7000	40.9639
70.0%	9.6667	1.3667	11.0333	88.2667	34.2939	2.4715	12.7000	38.8013
80.0%	9.6667	1.3667	11.0333	88.2667	36.3112	2.6168	12.7000	36.6386
90.0%	9.6667	1.3667	11.0333	88.2667	38.3285	2.7622	12.7000	34.4759
100.0%	9.6667	1.3667	11.0333	88.2667	40.3458	2.9076	12.7000	32.3133

Table 5.33 - Maximum Target Water Velocities with Increase in Pipe Constraint

Increase in Pipe Cstrt	**Pipe Cstrt** (ML/day)	**Discharge** (m3/s)	**Target Vmax** (m/s)
0.0%	290.00	3.3565	0.6366
2.5%	297.25	3.4404	0.6525
5.0%	304.50	3.5243	0.6684
7.5%	311.75	3.6082	0.6843
10.0%	319.00	3.6921	0.7002
12.5%	326.25	3.7760	0.7162
15.0%	333.50	3.8600	0.7321
17.5%	340.75	3.9439	0.7480
20.0%	348.00	4.0278	0.7639
22.5%	355.25	4.1117	0.7798
25.0%	362.50	4.1956	0.7957

Note: Cross-sectional Area for a (1372 + 1219) mm pipe = 5.2726 m2

Table 5.34 - Carlington Heights Branch (LI1W+FS1W) All Possible Electrical Pump Combinations

#	Fleet Street at least 3 pumps on	FS1W Capacity (ML/d)	Lemieux Island 1W pump comb.	LI1W Capacity (ML/d)	Total Capacity (ML/d)	Pipe Cstrt 290.0 ML/d
1	BBS	181.0	B	136.1	317.10	0
2		181.0	E	95.0	276.00	1
3		181.0	BB	272.2	453.20	0
4		181.0	BE	231.1	412.10	0
5		181.0	EE	190.0	371.00	0
6	BSS	131.3	B	136.1	267.40	1
7		131.3	E	95.0	226.30	1
8		131.3	BB	272.2	403.50	0
9		131.3	BE	231.1	362.40	0
10		131.3	EE	190.0	321.30	0
11	SSS	81.6	B	136.1	217.70	1
12		81.6	E	95.0	176.60	1
13		81.6	BB	272.2	353.80	0
14		81.6	BE	231.1	312.70	0
15		81.6	EE	190.0	271.60	1
16	BBSS	208.2	B	136.1	344.30	0
17		208.2	E	95.0	303.20	0
18		208.2	BB	272.2	480.40	0
19		208.2	BE	231.1	439.30	0
20		208.2	EE	190.0	398.20	0
21	BSSS	158.5	B	136.1	294.60	0
22		158.5	E	95.0	253.50	1
23		158.5	BB	272.2	430.70	0
24		158.5	BE	231.1	389.60	0
25		158.5	EE	190.0	348.50	0
26	BBSSS	235.4	B	136.1	371.50	0
27		235.4	E	95.0	330.40	0
28		235.4	BB	272.2	507.60	0
29		235.4	BE	231.1	466.50	0
30		235.4	EE	190.0	425.40	0

Table 5.35 - Carlington Heights Branch Electrical Pump Combinations
[BR1W, LI1W+FS1W, new (LI1W+FS1W), FS1W]

m	Pump Code	Capacity (ML/d)	Qm (ML/h)	Electrical Consumpt. (kW)	Um (kW.h/ML)	Um + trtmt base load (kW.h/ML)	
1	E	63.6	2.6500	597	225.28	305.28	
2	S	31.8	1.3250	336	253.58	333.58	
3	D	63.6	2.6500	671	253.21	333.21	
4	ES	95.4	3.9750	933	234.72	314.72	
5	ED	127.2	5.3000	1268	239.25	319.25	
6	SD	95.4	3.9750	1007	253.33	333.33	
7	ESD	159.0	6.6250	1604	242.11	322.11	
8	BBS-E	276.0	11.5000	2067	522.19	632.19	
9	BSS-B	267.4	11.1417	2134	376.31	486.31	
10	BSS-E	226.3	9.4292	1724	435.54	545.54	
11	SSS-B	217.7	9.0708	1791	315.83	425.83	
12	SSS-E	176.6	7.3583	1381	348.88	458.88	
13	SSS-EE	271.6	11.3167	3508	364.31	474.31	
14	BSSS-E	253.5	10.5625	1948	492.13	602.13	
(15)	BBS-B	317.1	13.2125	2477	436.80	546.80	10.0%
(16)	BSS-BE	362.4	15.1000	2843	295.25	405.25	25.0%
(17)	BSS-EE	321.3	13.3875	2433	307.33	417.33	12.5%
(18)	SSS-BB	353.8	14.7417	2910	256.63	366.63	22.5%
(19)	SSS-BE	312.7	13.0292	2500	259.63	369.63	10.0%
(20)	BBSS-B	344.3	14.3458	2701	476.30	586.30	20.0%
(21)	BBSS-E	303.2	12.6333	2291	578.78	688.78	5.0%
(22)	BSSS-B	294.6	12.2750	2358	415.81	525.81	2.5%
(23)	BSSS-EE	348.5	14.5208	2657	335.62	445.62	22.5%
(24)	BBSSS-E	330.4	13.7667	2515	635.37	745.37	15.0%
25	BBS	181.0	7.5417	1358	108.07	218.07	
26	BSS	131.3	5.4708	1015	185.53	295.53	
27	SSS	81.6	3.4000	672	197.65	307.65	
28	BBSS	208.2	8.6750	1582	182.36	292.36	
29	BSSS	158.5	6.6042	1239	187.61	297.61	
30	BBSSS	235.4	9.8083	1806	184.13	294.13	

Table 5.36 - Power Consumption Factors of Carlington Heights Branch
New Pump Combinations

Pump Combinations		Qtotal	U(Lemieux)	Q(Lemieux)	(QU)total	Increase
BBSS-E	X21	12.6333	179.12	3.9583	2098.67	5.0%
BBSSS-E	X24	13.7667	179.12	3.9583	2223.35	15.0%
BSSS-B	X22	12.2750	197.33	5.6708	2469.27	2.5%
BBS-B	X15	13.2125	197.33	5.6708	2572.39	10.0%
BBSS-B	X20	14.3458	197.33	5.6708	2697.06	20.0%
BSS-EE	X17	13.3875	179.12	7.9167	2890.66	12.5%
BSSS-EE	X23	14.5208	179.12	7.9167	3015.33	22.5%
SSS-BE	X19	13.0292	189.84	9.6292	3261.22	10.0%
BSS-BE	X16	15.1000	189.84	9.6292	3489.01	25.0%
SSS-BB	X18	14.7417	197.33	11.3417	3859.64	22.5%

Table 5.37 - Maximum Operating Volume of R2C Reservoir in Billings Bridge Branch with the Increase in Pipe Constraint

Increase in	Max. Pumping			Summer Night			Billings Bridge				Maximum
Pipe Cstrt	BR1W	Lemieux Isl.	Total Q	Night Q 8	Vk+HB+CH2W	FvTv @ R1W	BB XQ 8	BB Vk 23/4	BB XQ 6	BB Vk 6	BB FvTv 6
0.0%	6.6250	11.5000	18.1250	145.0000	96.1546	36.4137	12.4318	3.9917	8.4401	7.3400	1.1000
2.5%	6.6250	12.2750	18.9000	151.2000	96.1546	40.6000	14.4454	3.9917	10.4537	7.3400	3.1136
5.0%	6.6250	12.6333	19.2583	154.0664	96.1546	40.6000	17.3118	3.9917	13.3201	7.3400	5.9800
7.5%	6.6250	12.6333	19.2583	154.0664	96.1546	40.6000	17.3118	3.9917	13.3201	7.3400	5.9800
10.0%	6.6250	13.2125	19.8375	158.7000	96.1546	40.6000	21.9454	3.9917	17.9537	7.3400	10.6136
12.5%	6.6250	13.3875	20.0125	160.1000	96.1546	40.6000	23.3454	3.9917	19.3537	7.3400	12.0136
15.0%	6.6250	13.7667	20.3917	163.1336	96.1546	40.6000	26.3790	3.9917	22.3874	7.3400	15.0473
17.5%	6.6250	13.7667	20.3917	163.1336	96.1546	40.6000	26.3790	3.9917	22.3874	7.3400	15.0473
20.0%	6.6250	14.3458	20.9708	167.7664	96.1546	40.6000	31.0118	3.9917	27.0202	7.3400	19.6801
22.5%	6.6250	14.7417	21.3667	170.9336	96.1546	40.6000	34.1790	3.9917	30.1874	7.3400	22.8473
25.0%	6.6250	15.1000	21.7250	173.8000	96.1546	40.6000	37.0454	3.9917	33.0538	7.3400	25.7137

Table 5.38a - Maximum Operating Volume of R1E Reservoir in Hurdman Bridge Branch with Increasing Water Demand

Increase in Demand	Max Pump. HB1E	8 hours Night Q	8 hours Vk(HB1E)	Maximum FvTv(R1E)
0.0%	7.7250	61.8000	22.4096	39.3904
2.5%	7.7250	61.8000	22.9698	38.8302
5.0%	7.7250	61.8000	23.5301	38.2699
7.5%	7.7250	61.8000	24.0903	37.7097
10.0%	7.7250	61.8000	24.6506	37.1494
12.5%	7.7250	61.8000	25.2108	36.5892
15.0%	7.7250	61.8000	25.7710	36.0290
20.0%	7.7250	61.8000	26.8915	34.9085
30.0%	7.7250	61.8000	29.1325	32.6675
40.0%	7.7250	61.8000	31.3734	30.4266
50.0%	7.7250	61.8000	33.6144	28.1856

Table 5.38b - Maximum Operating Volume of R2C Reservoir in Billings Bridge Branch with Increasing Water Demand

Increase in Demand	Max Pump. BB2C	6 hours Night Q	6 hours Vk(BB2C)	Maximum FvTv(R2C)
0.0%	4.7417	28.4502	7.3400	39.3904
2.5%	4.7417	28.4502	7.5235	38.8302
5.0%	4.7417	28.4502	7.7070	38.2699
7.5%	4.7417	28.4502	7.8905	37.7097
10.0%	4.7417	28.4502	8.0740	37.1494
12.5%	4.7417	28.4502	8.2575	36.5892
15.0%	4.7417	28.4502	8.4410	36.0290
20.0%	4.7417	28.4502	8.8080	34.9085
30.0%	4.7417	28.4502	9.5420	32.6675
40.0%	4.7417	28.4502	10.2760	30.4266
50.0%	4.7417	28.4502	11.0100	28.1856

Table 5.39 - Maximum Operating Volume of R1W Reservoir in Carlington Heights Branch with Increasing Water Demand and Increase in Pipe Constraint of 25.0%

Increase in	Max. Pumping @ 1W			8 hours				Maximum
Demand	BR1W	Lemieux Isl.	Total Q	Night Q	Vk(CH1W)	XQ(HB1E)	XQ(BB2C)	FvTv (R1W)
0.0%	6.6250	15.1000	21.7250	173.8000	34.3546	60.2096	12.4317	66.8041
2.5%	6.6250	15.1000	21.7250	173.8000	35.2135	60.7698	12.6152	65.2015
5.0%	6.6250	15.1000	21.7250	173.8000	36.0723	61.3301	12.7987	63.5989
7.5%	6.6250	15.1000	21.7250	173.8000	36.9312	61.8000	12.9822	62.0866
10.0%	6.6250	15.1000	21.7250	173.8000	37.7901	61.8000	13.1657	61.0442
12.5%	6.6250	15.1000	21.7250	173.8000	38.6489	61.8000	13.3492	60.0019
15.0%	6.6250	15.1000	21.7250	173.8000	39.5078	61.8000	13.5327	58.9595
20.0%	6.6250	15.1000	21.7250	173.8000	41.2255	61.8000	13.8997	56.8748
30.0%	6.6250	15.1000	21.7250	173.8000	44.6610	61.8000	14.6337	52.7053
40.0%	6.6250	15.1000	21.7250	173.8000	48.0964	61.8000	15.3677	48.5359
50.0%	6.6250	15.1000	21.7250	173.8000	51.5319	61.8000	16.1017	44.3664
60.0%	6.6250	15.1000	21.7250	173.8000	54.9674	61.8000	16.1017	40.9309
70.0%	6.6250	15.1000	21.7250	173.8000	58.4028	61.8000	16.1017	37.4955
80.0%	6.6250	15.1000	21.7250	173.8000	61.8383	61.8000	16.1017	34.0600
90.0%	6.6250	15.1000	21.7250	173.8000	65.2737	61.8000	16.1017	30.6246
100.0%	6.6250	15.1000	21.7250	173.8000	68.7092	61.8000	16.1017	27.1891

Table 6.1 - Approximate Potential Energy Savings at the WPPs for Different Water Management Alternatives

Branch Water Management Alternative	Potential Energy Savings Approximate Yearly $
Glen Cairn/Stittsville	
Increasing R2W operating volume (Fig. 5.29)	
20% increase, approx. 5.62 ML	$22,116
40% increase, approx. 11.24 ML	$45,383
80% increase, approx. 22.49 ML	$89,560
Carlington Heights	
Increasing pipe constraint (Fig. 5.35)	
2.5% compared to 0.0%	$3,355
5.0% compared to 0.0%	$17,223
15.0% compared to 0.0%	$26,135
Increasing water demand (Fig. 5.39)	
(for a 15% increase in pipe constraint compared to 0.0%)	
10.0% increase in water demand	$47,319
20.0% increase in water demand	$73,507
10.0% increase in water demand	$99,092
Billings Bridge	
Increasing R2C operating volume (Fig. 5.37)	
(for a 5% increase in pipe constraint compared to 0.0% at Lemieux Island WPP)	
approx. 5.98 ML operating volume	$20,727

APPENDIX B

FIGURES

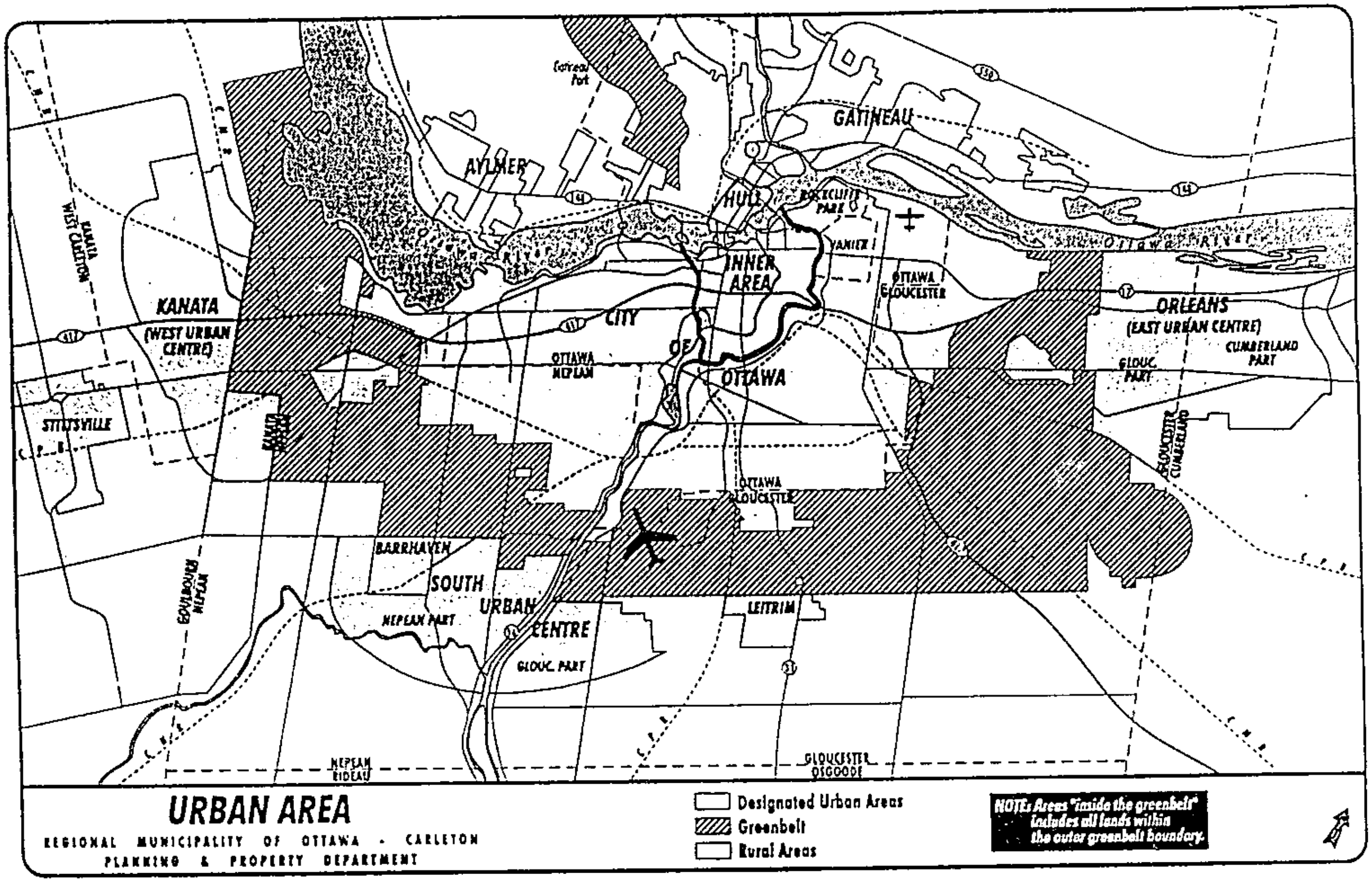

Figure 1.1a - Map of RMOC: Municipalities

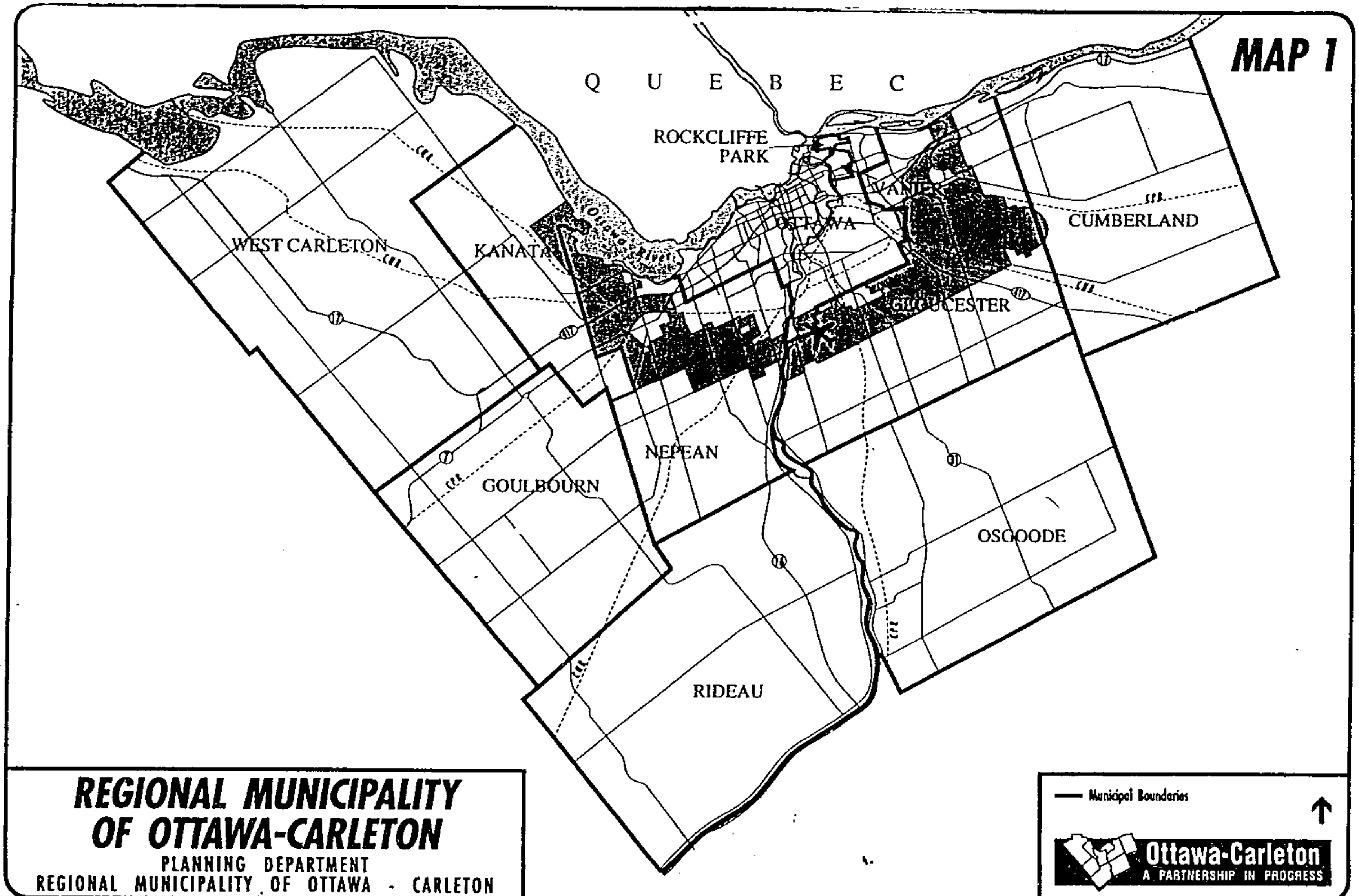

Figure 1.1b - Map of RMOC: Regional Growth

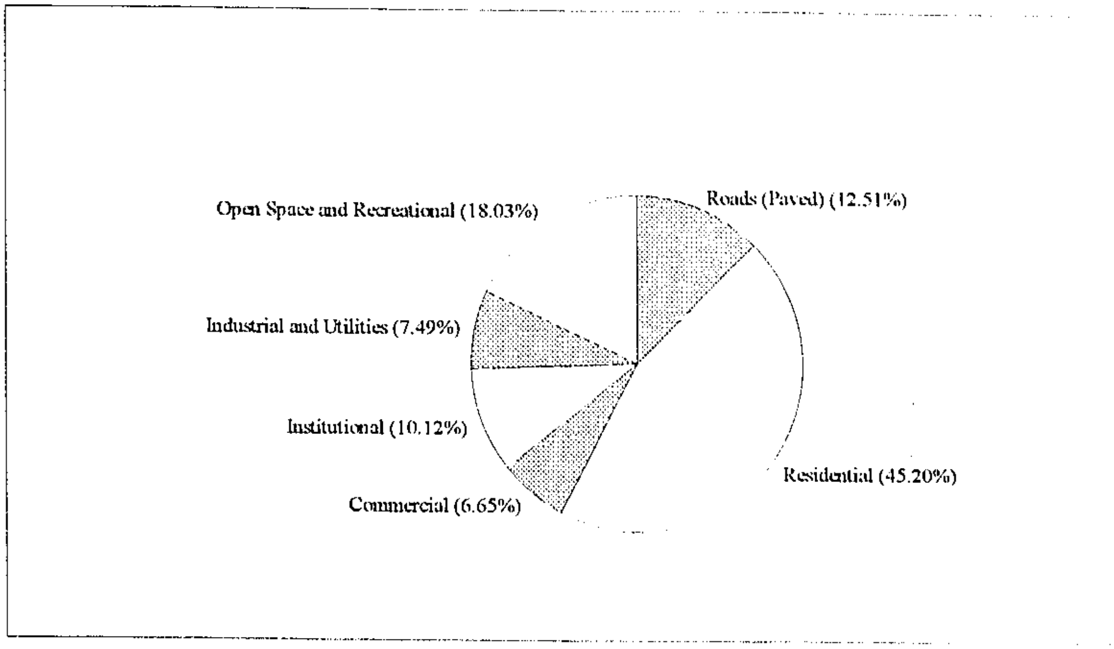

Figure 1.2 - Urban Land Uses in RMOC (1991)
(Source: RMOC, 1994)

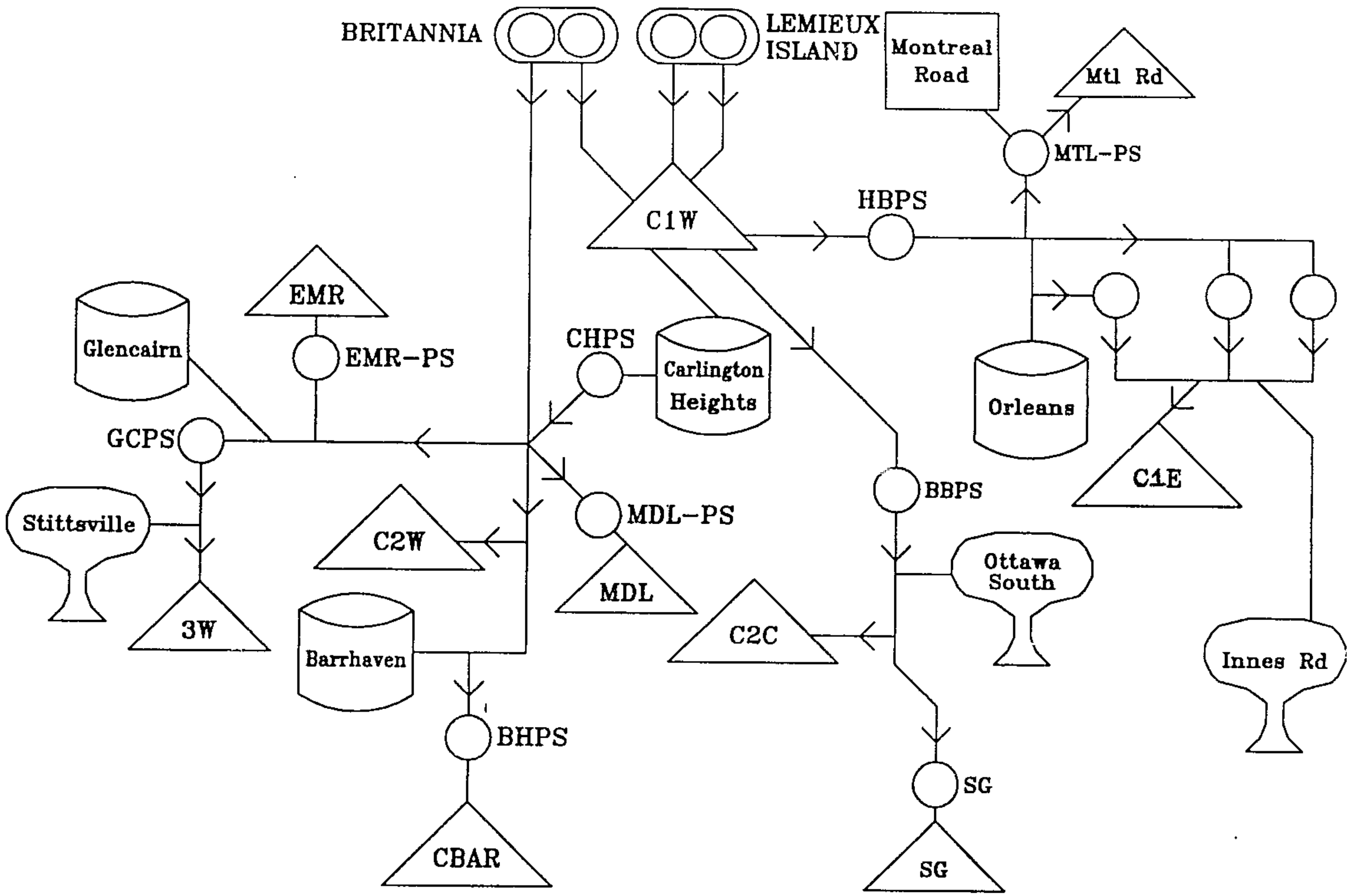

Figure 1.3 - RMOC's Water Supply Schematic

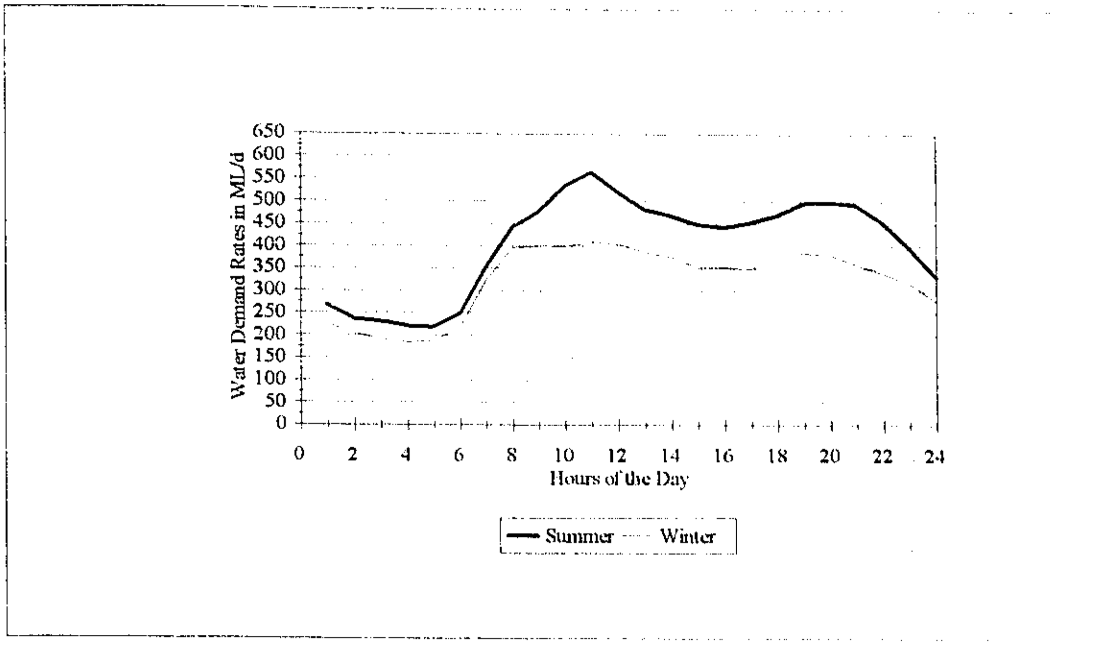

Figure 1.4 - Typical Water Demand Rates for RMOC

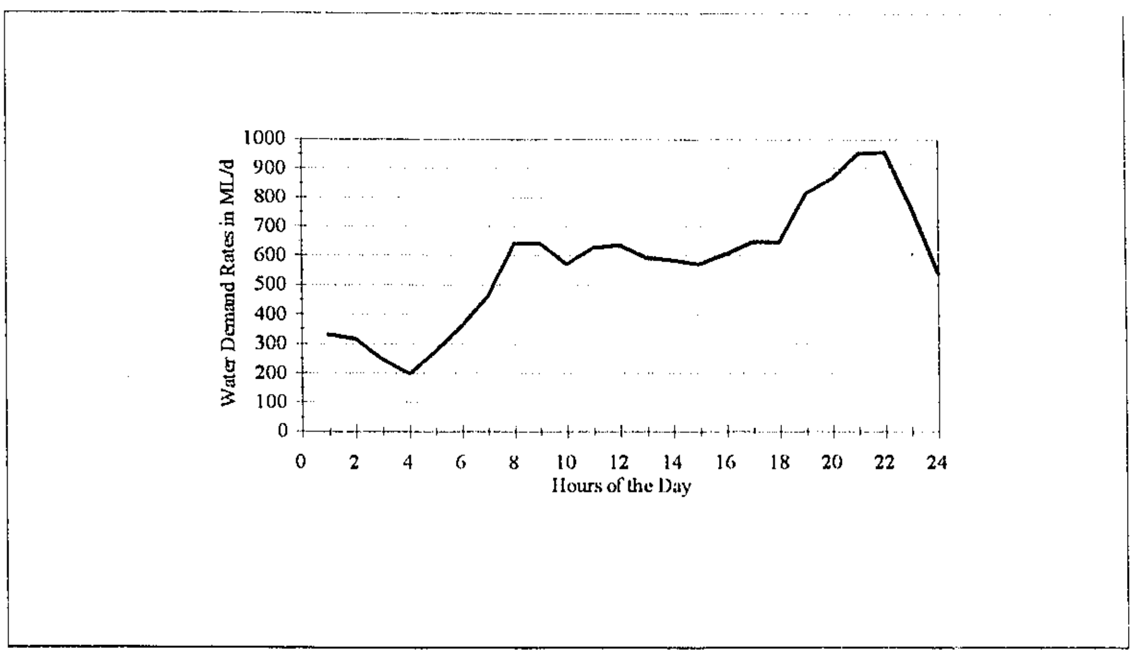

Figure 1.5 - Maximum Day in Summer: Water Demand Rates for RMOC (1991)

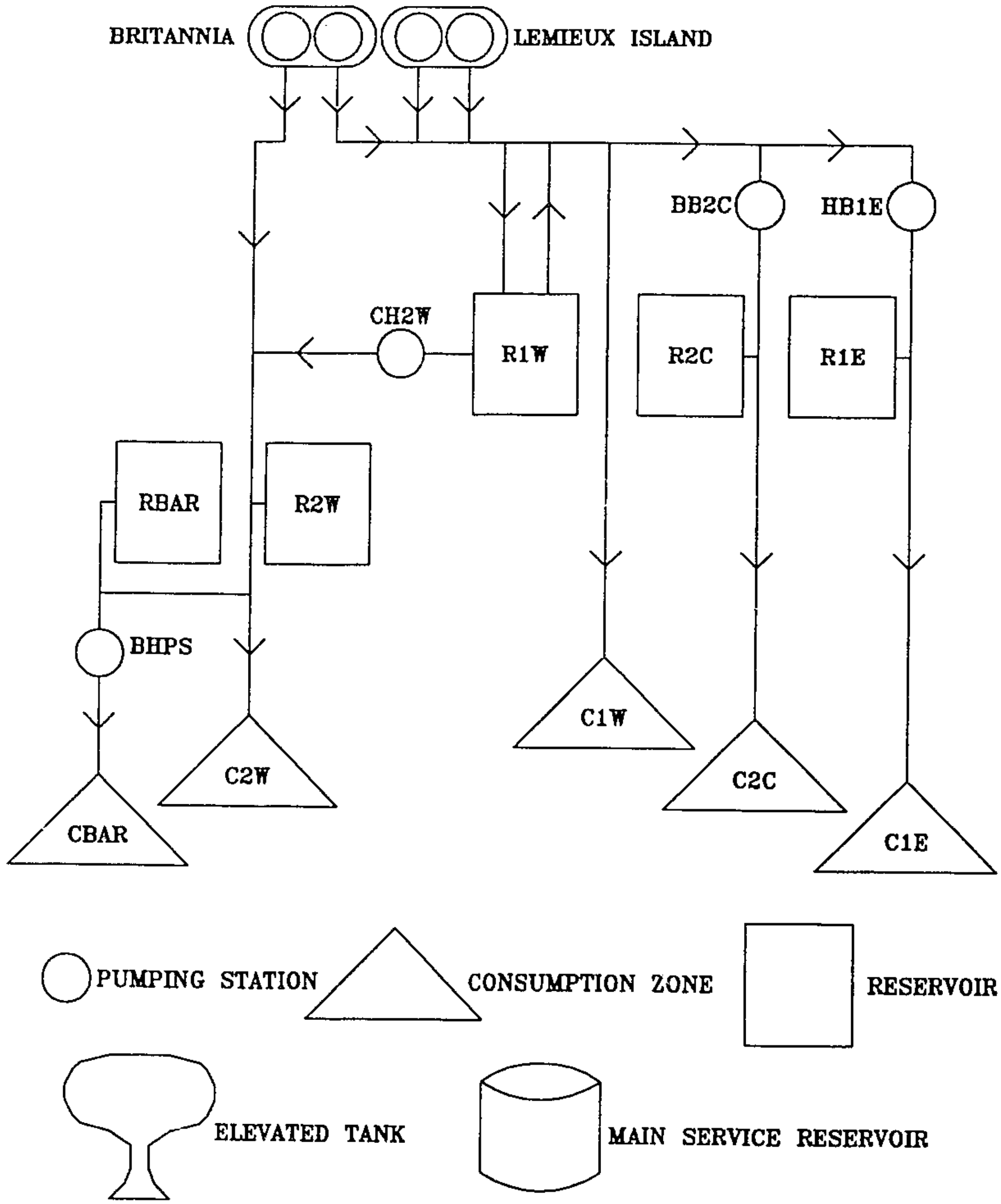

Figure 3.1 - RMOC's Network Schematic

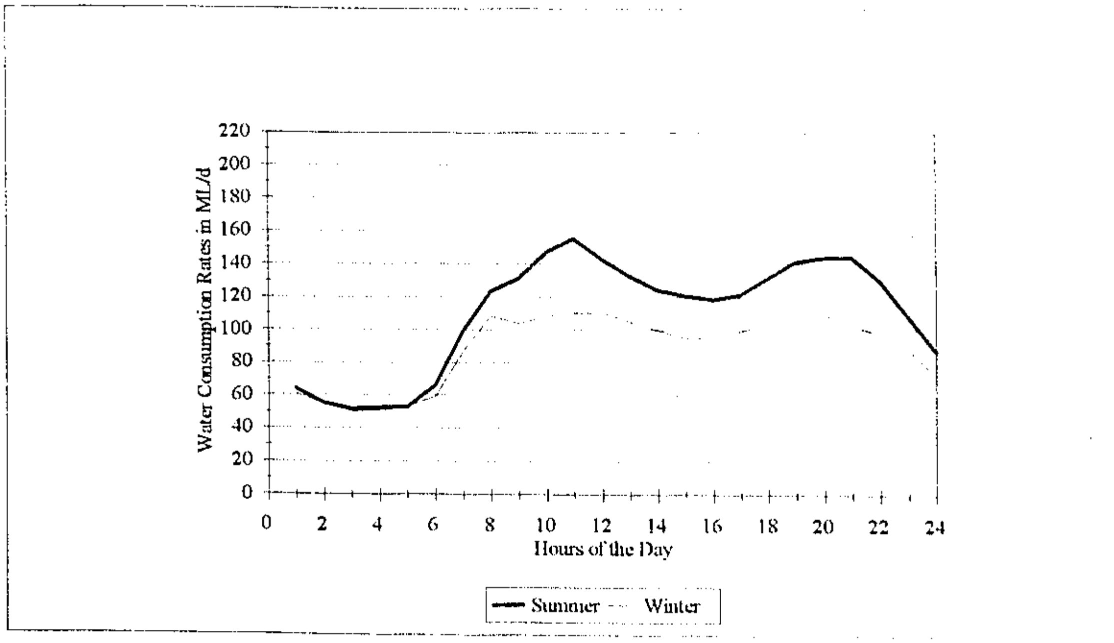

Figure 4.1 - Consumption Data for Hurdman Bridge Branch

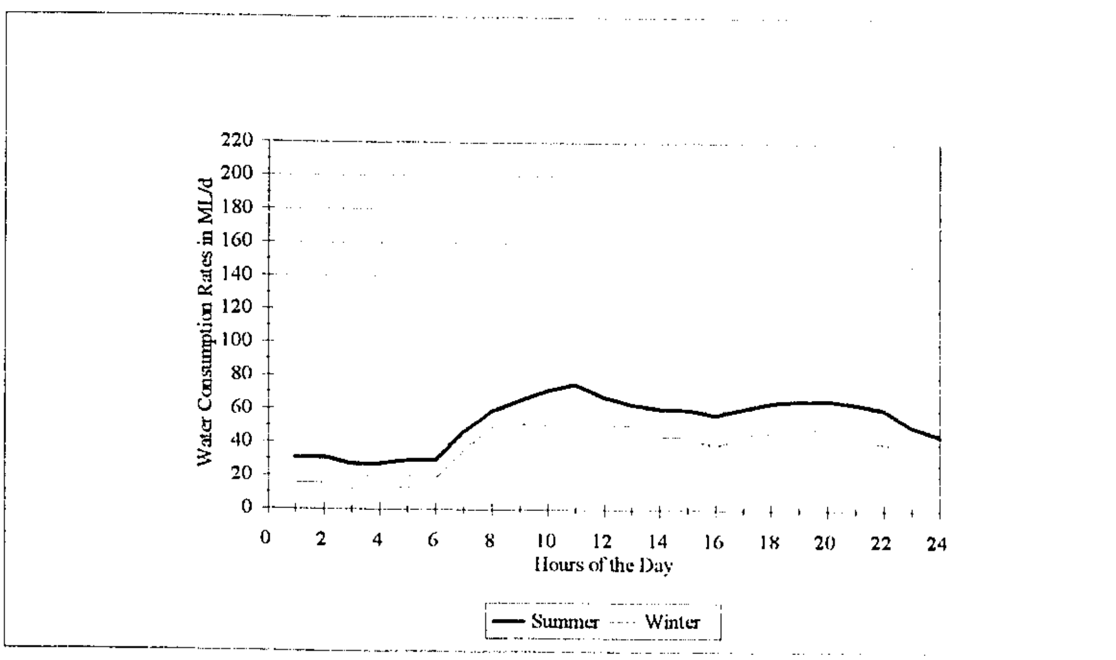

Figure 4.2 - Consumption Data for Billings Bridge Branch

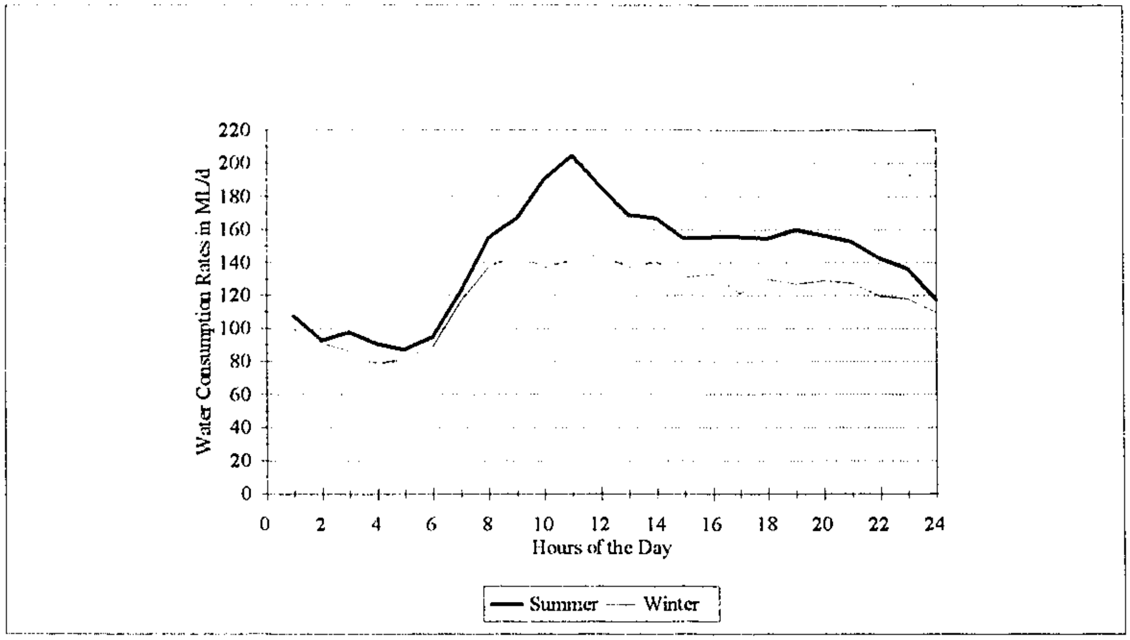

Figure 4.3 - Consumption Data for Carlington Heights Branch

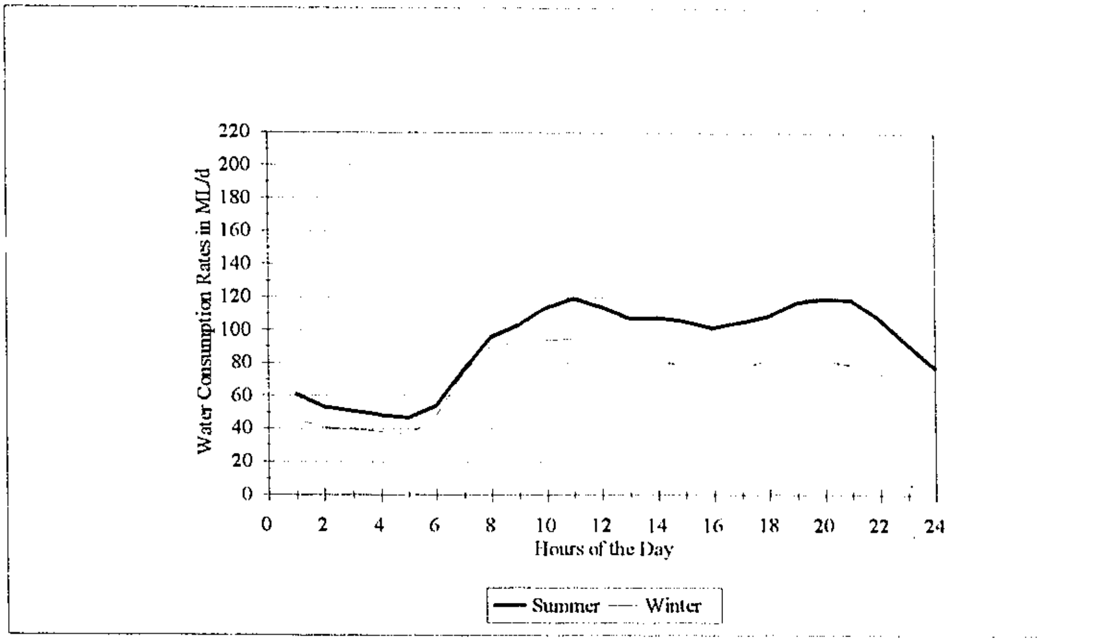

Figure 4.4a - Consumption Data for Glen Cairn/Stittsville Branch

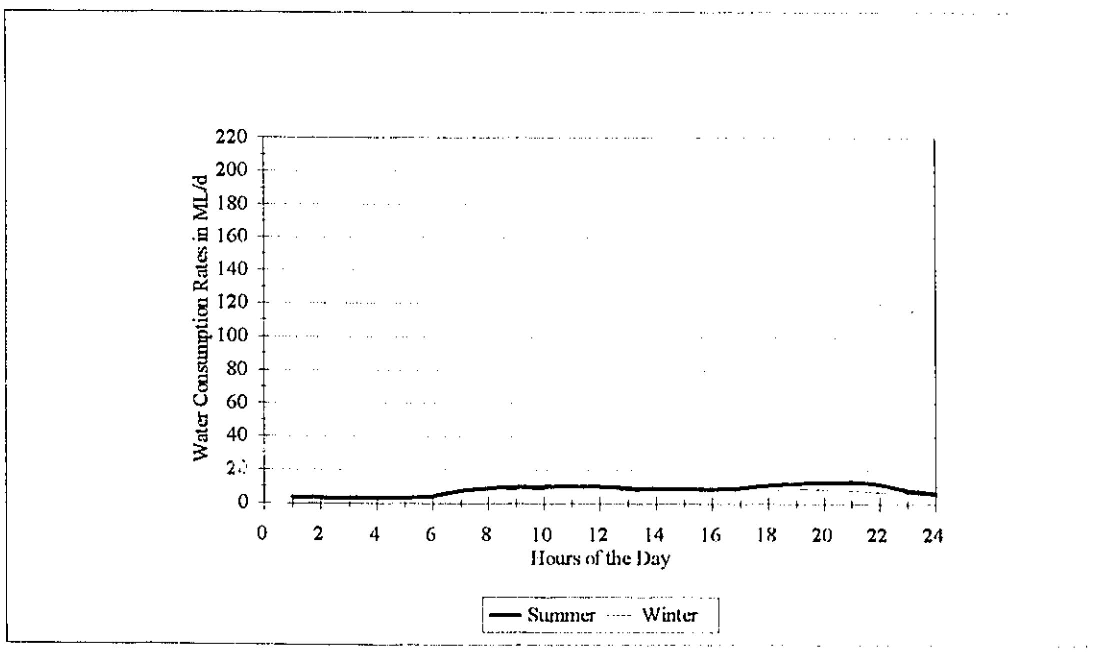

Figure 4.4b - Consumption Data for Barrhaven Sub-Branch

					Is the Pump Used?
Objective function:		f (X) =	273.61	$	
Pumping times:		X1 =	3.2429	hours	Yes
		X2 =	0.0000	hours	
		X3 =	0.0000	hours	
	BR2W	X4 =	0.0000	hours	
	$273.61	X5 =	4.7571	hours	Yes
		X6 =	0.0000	hours	
		X7 =	0.0000	hours	
		X8 =	0.0000	hours	
	CH2W	X9 =	0.0000	hours	
	$0.00	X10 =	0.0000	hours	
		Tvw =	2.1673	hours	
		Tvb =	5.2552	hours	

Reservoir storage:		Sw(k-1) =	23.8000	ML	Sw(min) =	23.8
		Sb(k-1) =	6.8000	ML	Sb(min) =	6.8
		Sw(k) =	38.7000	ML	Sw(max) =	38.7
		Sb(k) =	19.5001	ML	Sb(max) =	19.5
Fixed valve transfers:		FvwTvw =	14.9000	ML		
		FvbTvb =	12.7001	ML		
Water consumption:		Vw(k) =	20.1729	ML		
		Vb(k) =	1.4538	ML		
Total:	Zone 2W:	FvTv + Vk =	35.0729	ML		
	Zone BAR:	FvTv + Vk =	14.1539	ML		
		Total =	49.2268	ML		
Total water pumped:		BR2W: XQ =	38.2934	ML		
		CH2W: XQ =	10.9333	ML		
		Total =	49.2268	ML		

				Are Conditions Met?
Constraints	1a:	8.0000	<= 8	Yes
	1b:	8.0000	<= 8	Yes
	1c:	16.0000	>= 8	Yes
	2:	-0.0000	= 0	Yes
	3:	38.7000	>= 23.8	Yes
		19.5001	>= 6.8	Yes
		38.7000	<= 38.7	Yes
		19.5001	<= 19.5	Yes
	4:	38.7000	= 38.7	Yes
		19.5001	= 19.5	Yes
	5:	O.K.		

Figure 4.5 - Example of Level I Optimization Output
(Glen Cairn/Stittsville Branch for a Typical Summer Night)

GlenCairn 2W	k = 1	Summer
Solution Cell		
+D3	Minimize	0.0000
Variable Cells		
@COUNT(D4..D15)		
Constraints		
@COUNT(D4..D4)	>=	0.0000
@COUNT(D5..D5)	>=	0.0000
@COUNT(D6..D6)	>=	0.0000
@COUNT(D7..D7)	>=	0.0000
@COUNT(D8..D8)	>=	0.0000
@COUNT(D9..D9)	>=	0.0000
@COUNT(D10..D10)	>=	0.0000
@COUNT(D11..D11)	>=	0.0000
@COUNT(D12..D12)	>=	0.0000
@COUNT(D13..D13)	>=	0.0000
@COUNT(D14..D14)	>=	0.0000
@COUNT(D15..D15)	>=	0.0000
@COUNT(C34..C34)	<=	8.0000
@COUNT(C35..C35)	<=	8.0000
@COUNT(C36..C36)	>=	8.0000
@COUNT(C37..C37)	=	0.0000
@COUNT(C38..C38)	>=	23.8000
@COUNT(C39..C39)	>=	6.8000
@COUNT(C40..C40)	<=	38.7000
@COUNT(C41..C41)	<=	19.5000
@COUNT(C42..C42)	=	38.7000
@COUNT(C43..C43)	=	19.5000

Figure 4.6 - Example of Level I Linear Programming Formulation for "Optimizer" (Glen Cairn/Stittsville Branch for a Typical Summer Night)

Solution Cell	Night	Summer
+E78	Equal	0.0000
Variable Cells		
@COUNT(B70..C77)		
Constraints		
@COUNT(B70..C77)	>=	0.0000
@COUNT(E70..E77)	>=	0.0000
@COUNT(D70..D77)	=	1.0000
@COUNT(B78..B78)	=	3.2429
@COUNT(C78..C78)	=	4.7571

Figure 4.7 - Example of Level II Linear Programming Formulation for "Optimizer"
(Glen Cairn/Stittsville Branch for a Typical Summer Night)

			Is the Pump Used?
Objective function:	f(X) =	326.77 $	
Pumping times:	X1 =	0.4118 hours	Yes
	X2 =	7.5882 hours	Yes
	Tv =	4.5360 hours	
Reservoir storage:	S(k-1) =	51.9000 ML	S(min) = 51.9
	S(k) =	89.7000 ML	S(max) = 89.7
Fixed valve transfers:	FvTv =	37.8000 ML	
Water consumption:	Vk =	22.4096 ML	
Total:	FvTv + Vk:	60.2096 ML	
Total water pumped:	XQ =	60.2096 ML	

			Are Conditions Met?
Constraints	1:	8.0000 = 8	Yes
	2:	0.0000 = 0	Yes
	3:	89.7000 >= 51.9	Yes
		89.7000 <= 89.7	Yes
	4:	89.7000 = 89.7	Yes
	5:	O.K.	

Figure 5.1 - Hurdman Bridge Branch Level I Optimization - Summer Night

Objective function:	f (X) =	271.76	$	Is the Pump Used?
Pumping times:	X1 =	12.9643	hours	Yes
	X2 =	0.0000	hours	
	Tv =	4.5360	hours	
Reservoir storage:	S(k-1) =	89.7000	ML	S(min) = 51.9
	S(k) =	51.9000	ML	S(max) = 89.7
Fixed valve transfers:	FvTv =	37.8000	ML	
Water consumption:	Vk =	87.8746	ML	
Total:	Vk - FvTv:	50.0745	ML	
Total water pumped:	XQ =	50.0745	ML	

				Are Conditions Met?
Constraints	1:	12.9643	<= 16	Yes
	2:	0.0000	= 0	Yes
	3:	51.9000	>= 51.9	Yes
		51.9000	<= 89.7	Yes
	4:	51.9000	= 51.9	Yes
	5:	O.K.		

Figure 5.2 - Hurdman Bridge Branch Level I Optimization - Summer Day

			Is the Pump Used?
Objective function:	f(X) =	335.40 $	
Pumping times:	X1 =	0.0000 hours	
	X2 =	8.0000 hours	Yes
	Tv =	4.9662 hours	
Reservoir storage:	S(k-1) =	48.3154 ML*	S(min) = 41.7
	S(k) =	89.7000 ML	S(max) = 89.7
Fixed valve transfers:	FvTv =	41.3846 ML	
Water consumption:	Vk =	20.4154 ML	
Total:	FvTv + Vk:	61.8000 ML	
Total water pumped:	XQ =	61.8000 ML	

			Are Conditions Met?
Constraints	1:	8.0000 = 8	Yes
	2:	0.0000 = 0	Yes
	3:	89.7000 >= 41.7	Yes
		89.7000 <= 89.7	Yes
	4:	89.7000 = 89.7	Yes
	5:	O.K.	

Figure 5.3 - Hurdman Bridge Branch Level I Optimization - Winter Night

				Is the Pump Used?
Objective function:	f(X) =	148.87	$	
Pumping times:	X1 =	7.1016	hours	Yes
	X2 =	0.0000	hours	
	Tv =	4.9662	hours	
Reservoir storage:	S(k-1) =	89.7000	ML	S(min) = 41.7
	S(k) =	48.3154	ML	S(max) = 89.7
Fixed valve transfers:	FvTv =	41.3846	ML	
Water consumption:	Vk =	68.8146	ML	
Total:	Vk - FvTv:	27.4300	ML	
Total water pumped:	XQ =	27.4300	ML	

				Are Conditions Met?
Constraints	1:	7.1016	<= 16	Yes
	2:	0.0000	= 0	Yes
	3:	48.3154	>= 41.7	Yes
		48.3154	<= 89.7	Yes
	4:	48.3154	= 48.3154*	Yes
	5:	O.K.		

Figure 5.4 - Hurdman Bridge Branch Level I Optimization - Winter Day

				Is the Pump Used?		
Objective function:	f(X) =	69.26	$			
Pumping times:	X1 =	1.2000	hours	Yes		
	X2 =	4.8000	hours	Yes		
	X3 =	0.0000	hours			
	X4 =	0.0000	hours			
BB2C	X5 =	0.0000	hours			
	X6 =	0.0000	hours			
	X7 =	0.0000	hours			
	X8 =	0.0000	hours			
	X9 =	0.0000	hours			
	Tv =	0.7135	hours			
Reservoir storage:	S(k-1) =	2.3000	ML		S(min) =	2.3
	S(k) =	3.4000	ML		S(max) =	3.4
Fixed valve transfers:	FvTv =	1.1000	ML			
Water consumption:	Vk =	7.3400	ML			
Total:	FvTv + Vk:	8.4400	ML			
Total water pumped:	XQ =	8.4400	ML			

				Are Conditions Met?
Constraints	1:	6.0000	= 6	Yes
	2:	0.0000	= 0	Yes
	3:	3.4000	>= 2.3	Yes
		3.4000	<= 3.4	Yes
	4:	3.4000	= 3.4	Yes
	5:	O.K.		

Figure 5.5 - Billings Bridge Branch Level I Optimization - Summer Night

				Is the Pump Used?		
Objective function:		f(X) =	364.42 $			
Pumping times:		X1 =	0.0000 hours			
		X2 =	8.7225 hours	Yes		
		X3 =	0.0000 hours			
		X4 =	0.0000 hours			
	BB2C	X5 =	5.4662 hours	Yes		
		X6 =	0.0000 hours			
		X7 =	0.0000 hours			
		X8 =	3.0978 hours	Yes		
		X9 =	0.0000 hours			
		Tv =	0.7135 hours			
Reservoir storage:		S(k-1) =	3.4000 ML			
		S(k) =	2.3000 ML			
Fixed valve transfers:		FvTv =	1.1000 ML		S(min) =	2.3
Water consumption:		Vk =	46.0904 ML		S(max) =	3.4
Total:		Vk - FvTv:	44.9904 ML			
Total water pumped:		XQ =	44.9904 ML			

				Are Conditions Met?
Constraints	1:	17.2865	<= 18	Yes
	2:	0.0000	= 0	Yes
	3:	2.3000	>= 2.3	Yes
		2.3000	<= 3.4	Yes
	4:	2.3000	= 2.3	Yes
	5:	O.K.		

Figure 5.6 - Billings Bridge Branch Level I Optimization - Summer Day

				Is the Pump Used?
Objective function:		f(X) =	44.17 $	
Pumping times:		X1 =	6.0000 hours	Yes
		X2 =	0.0000 hours	
		X3 =	0.0000 hours	
		X4 =	0.0000 hours	
	BB2C	X5 =	0.0000 hours	
		X6 =	0.0000 hours	
		X7 =	0.0000 hours	
		X8 =	0.0000 hours	
		X9 =	0.0000 hours	
		Tv =	0.5838 hours	
Reservoir storage:		S(k-1) =	2.5000 ML	S(min) = 2.5
		S(k) =	3.4000 ML	S(max) = 3.4
Fixed valve transfers:		FvTv =	0.9000 ML	
Water consumption:		Vk =	3.7271 ML	
Total:		FvTv + Vk:	4.6271 ML	
Total water pumped:		XQ =	4.9000 ML	

				Are Conditions Met?
Constraints	1:	6.0000	= 6	Yes
	2:	0.2729	= 0	No
	3:	3.4000	>= 2.3	Yes
		3.4000	<= 3.4	Yes
	4:	3.4000	= 3.4	Yes
	5:	O.K.		

Figure 5.7 - Billings Bridge Branch Level I Optimization - Winter Night

				Is the Pump Used?
Objective function:	f(X) =	264.24	$	
Pumping times:	X1 =	0.0000	hours	
	X2 =	14.0880	hours	Yes
	X3 =	0.0000	hours	
	X4 =	0.0000	hours	
BB2C	X5 =	3.4512	hours	Yes
	X6 =	0.0000	hours	
	X7 =	0.0000	hours	
	X8 =	0.0000	hours	
	X9 =	0.0000	hours	
	Tv =	0.5838	hours	
Reservoir storage:	S(k-1) =	3.4000	ML	S(min) = 2.5
	S(k) =	2.5000	ML	S(max) = 3.4
Fixed valve transfers:	FvTv =	0.9000	ML	
Water consumption:	Vk =	33.5225	ML	
Total:	Vk - FvTv:	32.6225	ML	
Total water pumped:	XQ =	32.6225	ML	

				Are Conditions Met?
Constraints	1:	17.5392	<= 18	Yes
	2:	0.0000	= 0	Yes
	3:	2.5000	>= 2.5	Yes
		2.5000	<= 3.4	Yes
	4:	2.5000	= 2.5	Yes
	5:	O.K.		

Figure 5.8 - Billings Bridge Branch Level I Optimization - Winter Day

Objective function:		f (X) =	519.25 $	Is the Pump Used?
Pumping times:		X1 =	0.0000 hours	
		X2 =	0.0000 hours	
		X3 =	0.0000 hours	
	BR1W	X4 =	0.0000 hours	
	$269.74	X5 =	0.0000 hours	
		X6 =	0.0000 hours	
		X7 =	8.0000 hours	Yes
		X8 =	8.0000 hours	Yes
		X9 =	0.0000 hours	
	FS1W +	X10 =	0.0000 hours	
	LI1W	X11 =	0.0000 hours	
	$249.51	X12 =	0.0000 hours	
		X13 =	0.0000 hours	
		X14 =	0.0000 hours	
		X15 =	0.0000 hours	
		X16 =	0.0000 hours	
	FS1W	X17 =	0.0000 hours	
	$0.00	X18 =	0.0000 hours	
		X19 =	0.0000 hours	
		X20 =	0.0000 hours	
		Tv =	6.0807 hours	
Reservoir storage:		S(k-1) =	68.5000 ML	S(min) = 68.5
		S(k) =	106.5041 ML*	S(max) = 109.1
Fixed valve transfers:		FvTv =	38.0041 ML	
Water consumption:		Vk =	34.3546 ML	
		FvTv + Vk =	72.3586 ML	
		Hurdman1E:	60.2096 ML	
		Billings2C:	12.4317 ML	
		CH2W:	0.0000 ML	
		Total =	145.0000 ML	
Total water pumped:		BR1W XQ:	53.0000	
		LI/FS1W:	92.0000	
		FS1W XQ:	0.0000	
		XQ =	145.0000 ML	

Constraints				Are Conditions Met?
	1a:	8.0000	<= 8	Yes
	1b:	8.0000	<= 8	Yes
	1c:	16.0000	>= 8	Yes
	2:	0.0000	= 0	Yes
	3:	106.5041	>= 68.5	Yes
		106.5041	<= 109.1	Yes
	4:	106.5041	= 106.5041*	Yes
	5:	O.K.		

Figure 5.9 - Carlington Heights Branch Level I Optimization - Summer Night

Objective function:		f(X) =	1199.05 $	Is the Pump Used?
Pumping times:		X1 =	9.8428 hours	Yes
		X2 =	0.0000 hours	
		X3 =	0.0000 hours	
	BR1W	X4 =	0.0000 hours	
	$378.50	X5 =	0.0000 hours	
		X6 =	0.0000 hours	
		X7 =	0.0000 hours	
		X8 =	0.0000 hours	
		X9 =	0.0000 hours	
	FS1W +	X10 =	0.0000 hours	
	LI1W	X11 =	0.0000 hours	
	$0.00	X12 =	0.0000 hours	
		X13 =	0.0000 hours	
		X14 =	0.0000 hours	
		X15 =	0.0000 hours	
		X16 =	0.0000 hours	
	FS1W	X17 =	0.0000 hours	
	$820.55	X18 =	0.0000 hours	
		X19 =	0.0000 hours	
		X20 =	16.0000 hours	Yes
		Tv =	6.0807 hours	

Reservoir storage:	S(k-1) =	106.5041 ML*	S(min) =	68.5
	S(k) =	68.5000 ML	S(max) =	109.1
Fixed valve transfers:	FvTv =	38.0041 ML		
Water consumption:	Vk =	108.0808 ML		
	Vk - FvTv =	70.0768 ML		
	Hurdman1E:	50.0745 ML		
	Billings2C:	40.9989 ML		
	CH2W:	21.8667 ML		
	Total =	183.0168 ML		
Total water pumped:	BR1W XQ:	26.0834		
	LI/FS1W:	0.0000		
	FS1W XQ:	156.9333		
	XQ =	183.0168 ML		

				Are Conditions Met?
Constraints	1a:	9.8428	<= 16	Yes
	1b:	16.0000	<= 16	Yes
	2:	0.0000	= 0	Yes
	3:	68.5000	>= 68.5	Yes
		68.5000	<= 109.1	Yes
	4:	68.5000	= 68.5	Yes
	5:	O.K.		

Figure 5.10 - Carlington Heights Branch Level I Optimization - Summer Day

					Is the Pump Used?
Objective function:		f (X) =	755.87	$	
Pumping times:		X1 =	0.0000	hours	
		X2 =	0.0000	hours	
		X3 =	0.0000	hours	
	BR1W	X4 =	0.0000	hours	
	$392.66	X5 =	0.0000	hours	
		X6 =	0.0000	hours	
		X7 =	8.0000	hours	Yes
		X8 =	8.0000	hours	Yes
		X9 =	0.0000	hours	
	FS1W +	X10 =	0.0000	hours	
	LI1W	X11 =	0.0000	hours	
	$363.22	X12 =	0.0000	hours	
		X13 =	0.0000	hours	
		X14 =	0.0000	hours	
		X15 =	0.0000	hours	
		X16 =	0.0000	hours	
	FS1W	X17 =	0.0000	hours	
	$0.00	X18 =	0.0000	hours	
		X19 =	0.0000	hours	
		X20 =	0.0000	hours	
		Tv =	5.3454	hours	
Reservoir storage:		S(k-1) =	68.5000	ML	S(min) = 68.5
		S(k) =	101.9087	ML*	S(max) = 109.1
Fixed valve transfers:		FvTv =	33.4087	ML	
Water consumption:		Vk =	31.4233	ML	
		FvTv + Vk =	64.8320	ML	
		Hurdman1E:	61.8000	ML	
		Billings2C:	7.4346	ML	
		CH2W:	10.9333	ML	
		Total =	145.0000	ML	
Total water pumped:		BR1W XQ:	53.0000		
		LI/FS1W:	92.0000		
		FS1W XQ:	0.0000		
		XQ =	145.0000	ML	

				Are Conditions Met?
Constraints	1a:	8.0000	<= 8	Yes
	1b:	8.0000	<= 8	Yes
	1c:	16.0000	>= 8	Yes
	2:	0.0000	= 0	Yes
	3:	101.9087	>= 68.5	Yes
		101.9087	<= 109.1	Yes
	4:	101.9087	= 101.9087*	Yes
	5:	O.K.		

Figure 5.11 - Carlington Heights Branch Level I Optimization - Winter Night

				Is the Pump Used?
Objective function:		f (X) =	$850.55 $	
Pumping times:		X1 =	0.0000 hours	
		X2 =	0.0000 hours	
		X3 =	0.0000 hours	
	BR1W	X4 =	0.0000 hours	
	$0.00	X5 =	0.0000 hours	
		X6 =	0.0000 hours	
		X7 =	0.0000 hours	
		X8 =	0.0000 hours	
		X9 =	0.0000 hours	
	FS1W +	X10 =	0.0000 hours	
	LI1W	X11 =	0.0000 hours	
	$0.00	X12 =	0.0000 hours	
		X13 =	0.0000 hours	
		X14 =	0.0000 hours	
		X15 =	3.1030 hours	Yes
		X16 =	0.7715 hours	Yes
	FS1W	X17 =	0.0000 hours	
	$850.55	X18 =	3.9615 hours	Yes
		X19 =	2.3928 hours	Yes
		X20 =	5.7712 hours	Yes
		Tv =	5.3454 hours	

Reservoir storage:	S(k-1) =	101.9087 ML*	S(min) =	68.5
	S(k) =	68.5000 ML	S(max) =	109.1
Fixed valve transfers:	FvTv =	33.4087 ML		
Water consumption:	Vk =	88.4204 ML		
	Vk - FvTv =	55.0117 ML		
	Hurdman1E:	27.4300 ML		
	Billings2C:	30.0880 ML		
	CH2W:	21.8667 ML		
	Total =	134.3964 ML		
Total water pumped:	BR1W XQ:	0.0000		
	LI/FS1W:	0.0000		
	FS1W XQ:	134.3964		
	XQ =	134.3964 ML		

				Are Conditions Met?
Constraints	1a:	0.0000	<= 16	Yes
	1b:	16.0000	<= 16	Yes
	2:	0.0000	= 0	Yes
	3:	68.5000	>= 68.5	Yes
		68.5000	<= 109.1	Yes
	4:	68.5000	= 68.5	Yes
	5:	O.K.		

Figure 5.12 - Carlington Heights Branch Level I Optimization - Winter Day

					Is the Pump Used?
Objective function:		f(X) =	273.61	$	
Pumping times:		X1 =	3.2429	hours	Yes
		X2 =	0.0000	hours	
		X3 =	0.0000	hours	
	BR2W	X4 =	0.0000	hours	
	$273.61	X5 =	4.7571	hours	Yes
		X6 =	0.0000	hours	
		X7 =	0.0000	hours	
		X8 =	0.0000	hours	
	CH2W	X9 =	0.0000	hours	
	$0.00	X10 =	0.0000	hours	
		Tvw =	2.1673	hours	
		Tvb =	5.2552	hours	

Reservoir storage:		Sw(k-1) =	23.8000	ML	Sw(min) =	23.8
		Sb(k-1) =	6.8000	ML	Sb(min) =	6.8
		Sw(k) =	38.7000	ML	Sw(max) =	38.7
		Sb(k) =	19.5000	ML	Sb(max) =	19.5
Fixed valve transfers:		FvwTvw =	14.9000	ML		
		FvbTvb =	12.7000	ML		
Water consumption:		Vw(k) =	20.1729	ML		
		Vb(k) =	1.4538	ML		
Total:	Zone 2W:	FvTv + Vk =	35.0729	ML		
	Zone BAR:	FvTv + Vk =	14.1539	ML		
		Total =	49.2268	ML		
Total water pumped:		BR2W: XQ =	49.2268	ML		
		CH2W: XQ =	0.0000	ML		
		Total =	49.2268	ML		

				Are Conditions Met?
Constraints	1a:	8.0000	<= 8	Yes
	1b:	0.0000	<= 8	Yes
	1c:	8.0000	>= 8	Yes
	2:	0.0000	= 0	Yes
	3:	38.7000	>= 23.8	Yes
		19.5000	>= 6.8	Yes
		38.7000	<= 38.7	Yes
		19.5000	<= 19.5	Yes
	4:	38.7000	= 38.7	Yes
		19.5000	= 19.5	Yes
	5:	O.K.		

Figure 5.13 - Glen Cairn/Stittsville Branch Level I Optimization - Summer Night

					Is the Pump Used?		
Objective function:		f (X) =	649.14	$			
Pumping times:		X1 =	7.7566	hours	Yes		
		X2 =	0.0000	hours			
		X3 =	0.0000	hours			
	BR2W	X4 =	0.0000	hours			
	$481.89	X5 =	0.0000	hours			
		X6 =	0.0000	hours			
		X7 =	0.0000	hours			
		X8 =	0.0000	hours			
	CH2W	X9 =	0.0000	hours			
	$167.25	X10 =	16.0000	hours	Yes		
		Tvw =	2.1673	hours			
		Tvb =	5.2552	hours			
Reservoir storage:		Sw(k-1) =	38.7000	ML		Sw(min) =	23.8
		Sb(k-1) =	19.5001	ML		Sb(min) =	6.8
		Sw(k) =	23.8000	ML		Sw(max) =	38.7
		Sb(k) =	6.8000	ML		Sb(max) =	19.5
Fixed valve transfers:		FvwTvw =	14.9000	ML			
		FvbTvb =	12.7001	ML			
Water consumption:		Vw(k) =	71.7654	ML			
		Vb(k) =	6.7888	ML			
Total:	Water consumption (Vk) =		78.5542	ML			
	Fixed valve transf. (FvTv) =		27.6001	ML			
		Vk - FvTv =	50.9541	ML			
Total water pumped:		BR2W: XQ =	29.0874	ML			
		CH2W: XQ =	21.8667	ML			
		Total XQ =	50.9541	ML			

				Are Conditions Met?
Constraints	1a:	7.7566	<= 16	Yes
	1b:	16.0000	<= 16	Yes
	2:	0.0000	= 0	Yes
	3:	23.8000	>= 23.8	Yes
		6.8000	>= 6.8	Yes
		23.8000	<= 38.7	Yes
		6.8000	<= 19.5	Yes
	4:	23.8000	= 23.8	Yes
		6.8000	= 6.8	Yes
	5:	O.K.		

Figure 5.14 - Glen Cairn/Stittsville Branch Level I Optimization - Summer Day

					Is the Pump Used?		
Objective function:		f(X) =	353.88	$			
Pumping times:		X1 =	7.1026	hours	Yes		
		X2 =	0.0000	hours			
		X3 =	0.0000	hours			
	BR2W	X4 =	0.0000	hours			
	$270.26	X5 =	0.8974	hours	Yes		
		X6 =	0.0000	hours			
		X7 =	0.0000	hours			
		X8 =	0.0000	hours			
	CH2W	X9 =	0.0000	hours			
	$83.63	X10 =	8.0000	hours	Yes		
		Tvw =	2.1236	hours			
		Tvb =	5.2552	hours			
Reservoir storage:		Sw(k-1) =	24.1000	ML		Sw(min) =	24.1
		Sb(k-1) =	6.8000	ML		Sb(min) =	6.8
		Sw(k) =	38.7000	ML		Sw(max) =	38.7
		Sb(k) =	19.5000	ML		Sb(max) =	19.5
Fixed valve transfers:		FvwTvw =	14.6000	ML			
		FvbTvb =	12.7000	ML			
Water consumption:		Vw(k) =	15.9471	ML			
		Vb(k) =	1.3133	ML			
Total:	Zone 2W:	FvTv + Vk =	30.5471	ML			
	Zone BAR:	FvTv + Vk =	14.0133	ML			
		Total =	44.5604	ML			
Total water pumped:		BR2W: XQ =	33.6271	ML			
		CH2W: XQ =	10.9333	ML			
		Total =	44.5604	ML			

				Are Conditions Met?
Constraints	1a:	8.0000	<= 8	Yes
	1b:	8.0000	<= 8	Yes
	1c:	16.0000	>= 8	Yes
	2:	0.0000	= 0	Yes
	3:	38.7000	>= 24.1	Yes
		19.5000	>= 6.8	Yes
		38.7000	<= 38.7	Yes
		19.5000	<= 19.5	Yes
	4:	38.7000	= 38.7	Yes
		19.5000	= 19.5	Yes
	5:	O.K.		

Figure 5.15 - Glen Cairn/Stittsville Branch Level I Optimization - Winter Night

Objective function:	f (X) =	410.08	$	Is the Pump Used?
Pumping times:	X1 =	3.2292	hours	Yes
	X2 =	0.0000	hours	
	X3 =	0.0000	hours	
BR2W	X4 =	0.0000	hours	
$242.82	X5 =	0.0000	hours	
	X6 =	0.0000	hours	
	X7 =	0.0000	hours	
	X8 =	0.0000	hours	
CH2W	X9 =	0.0000	hours	
$167.25	X10 =	16.0000	hours	Yes
	Tvw =	2.1236	hours	
	Tvb =	5.2552	hours	
Reservoir storage:	Sw(k-1) =	38.7000	ML	Sw(min) = 24.1
	Sb(k-1) =	19.5000	ML	Sb(min) = 6.8
	Sw(k) =	24.1000	ML	Sk(max) = 38.7
	Sb(k) =	6.8000	ML	Sb(max) = 19.5
Fixed valve transfers:	FvwTvw =	14.6000	ML	
	FvbTvb =	12.7000	ML	
Water consumption:	Vw(k) =	56.0017	ML	
	Vb(k) =	5.2746	ML	
Total:	Water consumption (Vk) =	61.2763	ML	
	Fixed valve transf. (FvTv) =	27.3000	ML	
	Vk - FvTv =	33.9763	ML	
Total water pumped:	BR2W: XQ =	12.1096	ML	
	CH2W: XQ =	21.8667	ML	
	Total XQ =	33.9763	ML	

			Are Conditions Met?
Constraints	1a:	3.2292 <= 16	Yes
	1b:	16.0000 <= 16	Yes
	2:	0.0000 = 0	Yes
	3:	24.1000 >= 24.1	Yes
		6.8000 >= 6.8	Yes
		24.1000 <= 38.7	Yes
		6.8000 <= 19.5	Yes
	4:	24.1000 = 24.1	Yes
		6.8000 = 6.8	Yes
	5:	O.K.	

Figure 5.16 - Glen Cairn/Stittsville Branch Level I Optimization - Winter Day

			Is the Pump Used?
Objective function:	f(X) =	9.97 $	
Pumping times:	X1 =	0.0000 hours	
	X2 =	0.0000 hours	
	X3 =	0.0000 hours	
	X4 =	6.0000 hours	Yes
	X5 =	0.0000 hours	
	X6 =	0.0000 hours	
BHPS	X7 =	0.0000 hours	
	X8 =	0.0000 hours	
	X9 =	0.0000 hours	
	X10 =	0.0000 hours	
	X11 =	0.0000 hours	
	X12 =	0.0000 hours	
	X13 =	0.0000 hours	
Water consumption:	Vk =	0.8613 ML	
Total water pumped:	XQ =	1.1250 ML	

			Are Conditions Met?
Constraints	1:	6.0000 = 6	Yes
	2:	0.2638 = 0	No
	3:	O.K.	

Figure 5.17 - Barrhaven Sub-Branch Level I Optimization - Summer Night

			Is the Pump Used?
Objective function:	f(X) =	70.10 $	
Pumping times:	X1 =	0.0000 hours	
	X2 =	0.0000 hours	
	X3 =	0.0000 hours	
	X4 =	15.2211 hours	Yes
	X5 =	0.0000 hours	
	X6 =	0.0000 hours	
BHPS	X7 =	0.0000 hours	
	X8 =	2.7790 hours	Yes
	X9 =	0.0000 hours	
	X10 =	0.0000 hours	
	X11 =	0.0000 hours	
	X12 =	0.0000 hours	
	X13 =	0.0000 hours	
Water consumption:	Vk =	7.3813 ML	
Total water pumped:	XQ =	7.3813 ML	

			Are Conditions Met?
Constraints	1:	18.0000 = 18	Yes
	2:	0.0001 = 0	No
	3:	O.K.	

Figure 5.18 - Barrhaven Sub-Branch Level I Optimization - Summer Day

			Is the Pump Used?
Objective function:	f(X) =	9.97 $	
Pumping times:	X1 =	0.0000 hours	
	X2 =	0.0000 hours	
	X3 =	0.0000 hours	
	X4 =	6.0000 hours	Yes
	X5 =	0.0000 hours	
	X6 =	0.0000 hours	
BHPS	X7 =	0.0000 hours	
	X8 =	0.0000 hours	
	X9 =	0.0000 hours	
	X10 =	0.0000 hours	
	X11 =	0.0000 hours	
	X12 =	0.0000 hours	
	X13 =	0.0000 hours	
Water consumption:	Vk =	0.8363 ML	
Total water pumped:	XQ =	1.1250 ML	

			Are Conditions Met?
Constraints	1:	6.0000 = 6	Yes
	2:	0.2888 = 0	No
	3:	O.K.	

Figure 5.19 - Barrhaven Sub-Branch Level I Optimization - Winter Night

				Is the Pump Used?
Objective function:		f(X) =	53.75 $	
Pumping times:		X1 =	0.0000 hours	
		X2 =	0.0000 hours	
		X3 =	0.0000 hours	
		X4 =	16.3516 hours	Yes
		X5 =	0.0000 hours	
		X6 =	0.0000 hours	
	BHPS	X7 =	0.0000 hours	
		X8 =	1.6485 hours	Yes
		X9 =	0.0000 hours	
		X10 =	0.0000 hours	
		X11 =	0.0000 hours	
		X12 =	0.0000 hours	
		X13 =	0.0000 hours	
Water consumption:		Vk =	5.7517 ML	
Total water pumped:		XQ =	5.7517 ML	

			Are Conditions Met?
Constraints	1:	18.0000 = 18	Yes
	2:	0.0000 = 0	Yes
	5:	O.K.	

Figure 5.20 - Barrhaven Sub-Branch Level I Optimization - Winter Day

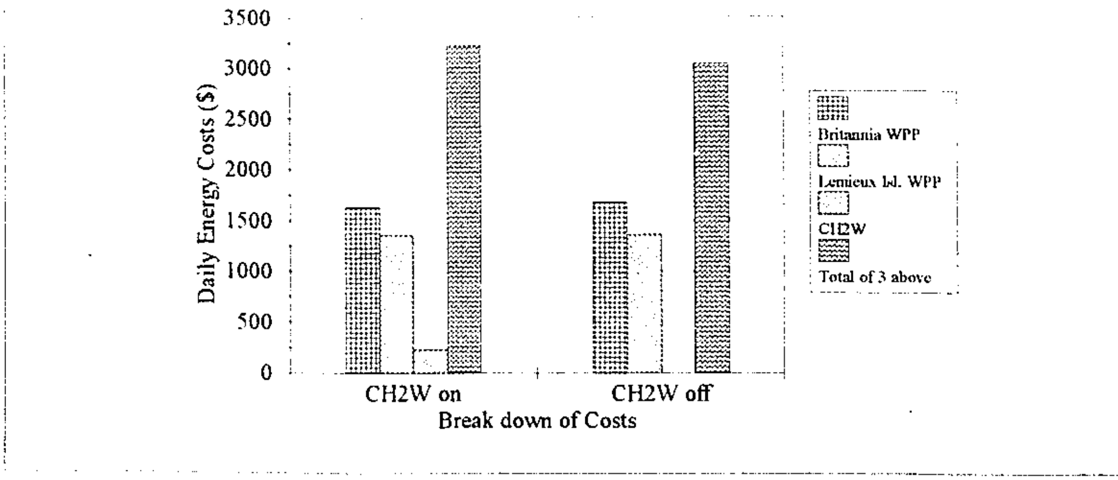

Figure 5.21 - Energy Costs for a Typical Summer Day with CH2W On or Off

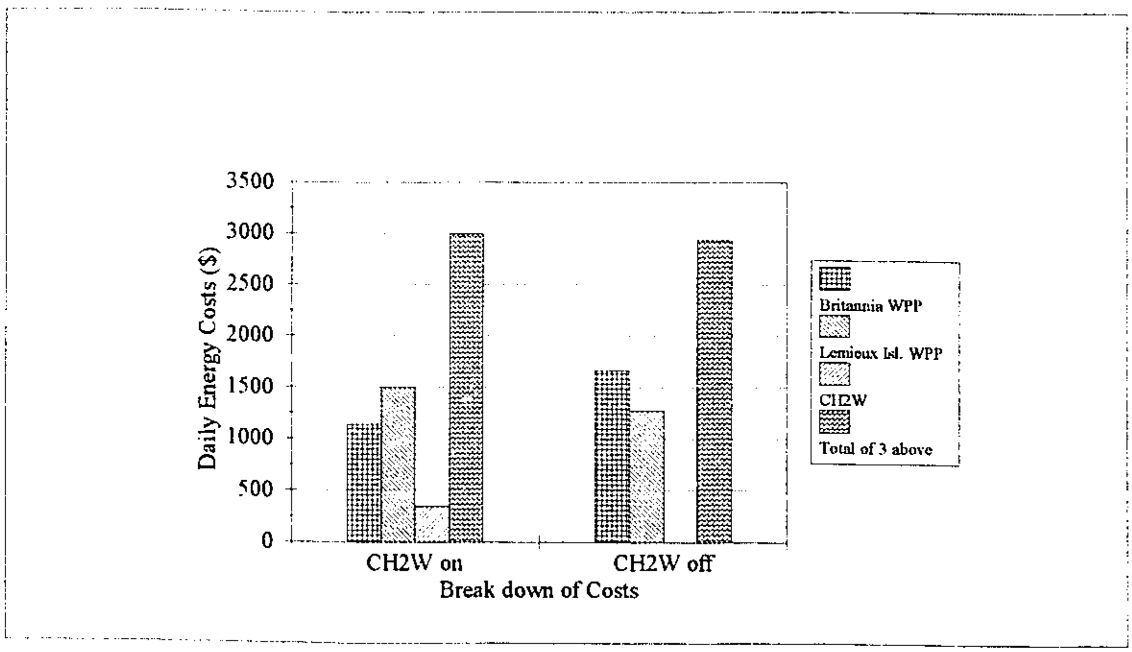

Figure 5.22 - Energy Costs for a Typical Winter Day with CH2W On or Off

Objective function:		f(X) =	844.16 $	Is the Pump Used?	
Pumping times:		X1 =	13.5878 hours	Yes	
		X2 =	0.0000 hours		
		X3 =	0.0000 hours		
	BR2W	X4 =	0.0000 hours		
	$844.16	X5 =	0.0000 hours		
		X6 =	0.0000 hours		
		X7 =	0.0000 hours		
		X8 =	0.0000 hours		
	CH2W	X9 =	0.0000 hours		
	$0.00	X10 =	0.0000 hours		
		Tvw =	2.1673 hours		
		Tvb =	5.2552 hours		
Reservoir storage volumes:		Sw(k-1) =	38.7000 ML	Sw(min) =	23.8
		Sb(k-1) =	19.5000 ML	Sb(min) =	6.8
		Sw(k) =	23.8000 ML	Sw(max) =	38.7
		Sb(k) =	6.8000 ML	Sb(max) =	19.5
Fixed valve transfers:		FvwTvw =	14.9000 ML		
		FvbTvb =	12.7000 ML		
Water consumption:		Vw(k) =	71.7654 ML		
		Vb(k) =	6.7888 ML		
Total:	Water consumption (Vk) =		78.5542 ML		
	Fixed valve transf. (FvTv) =		27.6000 ML		
		Vk - FvTv =	50.9542 ML		
Total water pumped:		BR2W: XQ =	50.9542 ML		
		CH2W: XQ =	0.0000 ML		
		Total XQ =	50.9542 ML		

				Are Conditions Met?
Constraints	1a:	13.5878	<= 16	Yes
	1b:	0.0000	<= 16	Yes
	2:	-0.0000	= 0	Yes
	3:	23.8000	>= 23.8	Yes
		6.8000	>= 6.8	Yes
		23.8000	<= 38.7	Yes
		6.8000	<= 19.5	Yes
	4:	23.8000	= 23.8	Yes
		6.8000	= 6.8	Yes
	5:	O.K.		

Figure 5.23 - Glen Cairn/Stittsville Branch Level I Optimization - Summer Day with CH2W Offline

					Is the Pump Used?
Objective function:		f(X) =	360.00	$	
Pumping times:		X1 =	4.3974	hours	Yes
		X2 =	0.0000	hours	
		X3 =	0.0000	hours	
	BR2W	X4 =	0.0000	hours	
	$360.00	X5 =	3.6026	hours	Yes
		X6 =	0.0000	hours	
		X7 =	0.0000	hours	
		X8 =	0.0000	hours	
	CH2W	X9 =	0.0000	hours	
	$0.00	X10 =	0.0000	hours	
		Tvw =	2.1236	hours	
		Tvb =	5.2552	hours	

Reservoir storage volumes:		Sw(k-1) =	24.1000	ML	Sw(min) =	24.1
		Sb(k-1) =	6.8000	ML	Sb(min) =	6.8
		Sw(k) =	38.7000	ML	Sw(max) =	38.7
		Sb(k) =	19.5000	ML	Sb(max) =	19.5
Fixed valve transfers:		FvwTvw =	14.6000	ML		
		FvbTvb =	12.7000	ML		
Water consumption:		Vw(k) =	15.9471	ML		
		Vb(k) =	1.3133	ML		
Total:	Zone 2W:	FvTv + Vk =	30.5471	ML		
	Zone BAR:	FvTv + Vk =	14.0133	ML		
		Total =	44.5604	ML		
Total water pumped:		BR2W: XQ =	44.5605	ML		
		CH2W: XQ =	0.0000	ML		
		Total =	44.5605	ML		

				Are Conditions Met?
Constraints	1a:	8.0000	<= 8	Yes
	1b:	0.0000	<= 8	Yes
	1c:	8.0000	>= 8	Yes
	2:	0.0000	= 0	Yes
	3:	38.7000	>= 24.1	Yes
		19.5000	>= 6.8	Yes
		38.7000	<= 38.7	Yes
		19.5000	<= 19.5	Yes
	4:	38.7000	= 38.7	Yes
		19.5000	= 19.5	Yes
	5:	O.K.		

Figure 5.24 - Glen Cairn/Stittsville Branch Level I Optimization - Winter Night with CH2W Offline

				Is the Pump Used?		
Objective function:		f(X) =	681.30 $			
Pumping times:		X1 =	9.0604 hours	Yes		
		X2 =	0.0000 hours			
		X3 =	0.0000 hours			
	BR2W	X4 =	0.0000 hours			
	$681.30	X5 =	0.0000 hours			
		X6 =	0.0000 hours			
		X7 =	0.0000 hours			
		X8 =	0.0000 hours			
	CH2W	X9 =	0.0000 hours			
	$0.00	X10 =	0.0000 hours			
		Tvw =	2.1236 hours			
		Tvb =	5.2552 hours			
Reservoir storage volumes:		Sw(k-1) =	38.7000 ML		Sw(min) =	24.1
		Sb(k-1) =	19.5000 ML		Sb(min) =	6.8
		Sw(k) =	24.1000 ML		Sk(max) =	38.7
		Sb(k) =	6.8000 ML		Sb(max) =	19.5
Fixed valve transfers:		FvwTvw =	14.6000 ML			
		FvbTvb =	12.7000 ML			
Water consumption:		Vw(k) =	56.0017 ML			
		Vb(k) =	5.2746 ML			
Total:	Water consumption (Vk) =		61.2763 ML			
	Fixed valve transf. (FvTv) =		27.3000 ML			
		Vk - FvTv =	33.9763 ML			
Total water pumped:		BR2W: XQ =	33.9764 ML			
		CH2W: XQ =	0.0000 ML			
		Total XQ =	33.9764 ML			

				Are Conditions Met?
Constraints	1a:	9.0604	<= 16	Yes
	1b:	0.0000	<= 16	Yes
	2:	0.0000	= 0	Yes
	3:	24.1000	>= 24.1	Yes
		6.8000	>= 6.8	Yes
		24.1000	<= 38.7	Yes
		6.8000	<= 19.5	Yes
	4:	24.1000	= 24.1	Yes
		6.8000	= 6.8	Yes
	5:	O.K.		

Figure 5.25 - Glen Cairn/Stittsville Branch Level I Optimization - Winter Day with CH2W Offline

				Is the Pump Used?
Objective function:	f (X) =	881.74	$	
Pumping times:	X1 =	1.5912	hours	Yes
	X2 =	0.0000	hours	
	X3 =	0.0000	hours	
BR1W	X4 =	0.0000	hours	
$61.19	X5 =	0.0000	hours	
	X6 =	0.0000	hours	
	X7 =	0.0000	hours	
	X8 =	0.0000	hours	
	X9 =	0.0000	hours	
FS1W +	X10 =	0.0000	hours	
LI1W	X11 =	0.0000	hours	
$0.00	X12 =	0.0000	hours	
	X13 =	0.0000	hours	
	X14 =	0.0000	hours	
	X15 =	0.0000	hours	
	X16 =	0.0000	hours	
FS1W	X17 =	0.0000	hours	
$820.55	X18 =	0.0000	hours	
	X19 =	0.0000	hours	
	X20 =	16.0000	hours	Yes
	Tv =	6.0807	hours	
Reservoir storage volumes:	S(k-1) =	106.5041	ML	S(min) = 68.5
	S(k) =	68.5000	ML	S(max) = 109.1
Fixed valve transfers:	FvTv =	38.0041	ML	
Water consumption:	Vk =	108.0808	ML	
	Vk - FvTv =	70.0768	ML	
	Hurdman1E:	50.0745	ML	
	Billings2C:	40.9989	ML	
	CH2W:	0.0000	ML	
	Total =	161.1501	ML	
Total water pumped:	BR1W XQ:	4.2168		
	LI/FS1W:	0.0000		
	FS1W XQ:	156.9333		
	XQ =	161.1501	ML	

Constraints				Are Conditions Met?
	1a:	1.5912	<= 16	Yes
	1a:	16.0000	<= 16	Yes
	2:	-0.0000	= 0	Yes
	3:	68.5000	>= 68.5	Yes
		68.5000	<= 109.1	Yes
	4:	68.5000	= 68.5	Yes
	5:	O.K.		

Figure 5.26- Carlington Heights Branch Level I Optimization - Summer Day with CH2W Offline

					Is the Pump Used?
Objective function:		f (X) =	710.33	$	
Pumping times:		X1 =	0.0000	hours	
		X2 =	0.0000	hours	
		X3 =	0.0000	hours	
	BR1W	X4 =	0.0000	hours	
	$392.66	X5 =	0.0000	hours	
		X6 =	0.0000	hours	
		X7 =	8.0000	hours	Yes
		X8 =	5.7880	hours	Yes
		X9 =	0.0000	hours	
	FS1W + LI1W	X10 =	0.0000	hours	
		X11 =	0.0000	hours	
	$262.78	X12 =	0.0000	hours	
		X13 =	0.0000	hours	
		X14 =	0.0000	hours	
		X15 =	0.0000	hours	
		X16 =	0.0000	hours	
	FS1W	X17 =	0.0000	hours	
	$54.89	X18 =	0.0000	hours	
		X19 =	0.0000	hours	
		X20 =	2.2120	hours	Yes
		Tv =	6.4960	hours	

Reservoir storage volumes:	S(k-1) =	68.5000	ML	S(min) =	68.5
	S(k) =	109.1000	ML	S(max) =	109.1
Fixed valve transfers:	FvTv =	40.6000	ML		
Water consumption:	Vk =	31.4233	ML		
	FvTv + Vk =	72.0233	ML		
	Hurdman1E:	61.8000	ML		
	Billings2C:	7.4346	ML		
	CH2W:	0.0000	ML		
	Total =	141.2580	ML		
Total water pumped:	BR1W XQ:	53.0000			
	LI/FS1W:	66.5614			
	FS1W XQ:	21.6965			
	XQ =	141.2579	ML		

				Are Conditions Met?
Constraints	1a:	8.0000	<= 8	Yes
	1b:	8.0000	<= 8	Yes
	1c:	16.0000	>= 8	Yes
	2:	-0.0000	= 0	Yes
	3:	109.1000	>= 68.5	Yes
		109.1000	<= 109.1	Yes
	4:	109.1000	= 109.1	Yes
	5:	O.K.		

Figure 5.27- Carlington Heights Branch Level I Optimization - Winter Night with CH2W Offline

Objective function:		f (X) =	666.65 $	Is the Pump Used?
Pumping times:		X1 =	0.0000 hours	
		X2 =	0.0000 hours	
		X3 =	0.0000 hours	
	BR1W	X4 =	0.0000 hours	
	$0.00	X5 =	0.0000 hours	
		X6 =	0.0000 hours	
		X7 =	0.0000 hours	
		X8 =	0.0000 hours	
		X9 =	0.0000 hours	
	FS1W +	X10 =	0.0000 hours	
	LI1W	X11 =	0.0000 hours	
	$0.00	X12 =	0.0000 hours	
		X13 =	0.0000 hours	
		X14 =	0.0000 hours	
		X15 =	4.3192 hours	Yes
		X16 =	5.7450 hours	Yes
	FS1W	X17 =	0.0000 hours	
	$666.65	X18 =	1.0303 hours	Yes
		X19 =	4.9056 hours	Yes
		X20 =	0.0000 hours	
		Tv =	6.4960 hours	
Reservoir storage volumes:		S(k-1) =	109.1000 ML	S(min) = 68.5
		S(k) =	68.5000 ML	S(max) = 109.1
Fixed valve transfers:		FvTv =	40.6000 ML	
Water consumption:		Vk =	88.4204 ML	
		Vk - FvTv =	47.8204 ML	
		Hurdman1E:	27.4300 ML	
		Billings2C:	30.0880 ML	
		CH2W:	0.0000 ML	
		Total =	105.3384 ML	
Total water pumped:		BR1W XQ:	0.0000	
		LI/FS1W:	0.0000	
		FS1W XQ:	105.3384	
		XQ =	105.3384 ML	

				Are Conditions Met?
Constraints	1a:	0.0000	<= 16	Yes
	1b:	16.0000	<= 16	Yes
	2:	-0.0000	= 0	Yes
	3:	68.5000	>= 68.5	Yes
		68.5000	<= 109.1	Yes
	4:	68.5000	= 68.5	Yes
	5:	O.K.		

Figure 5.28- Carlington Heights Branch Level I Optimization - Winter Day with CH2W Offline

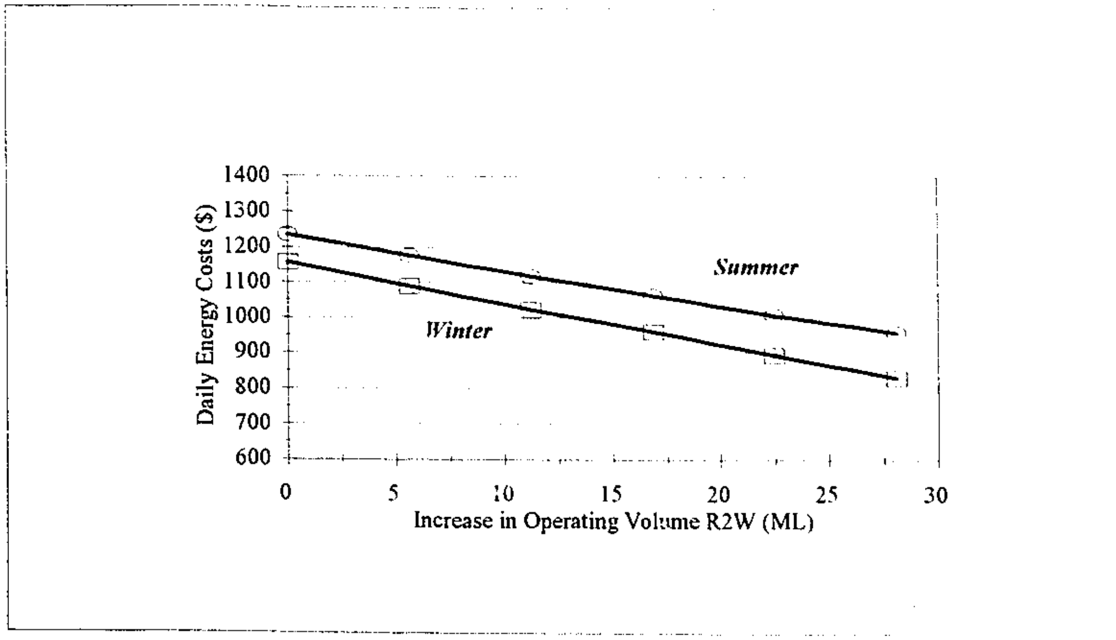

Figure 5.29 - Glen Cairn/Stittsville Branch Energy Costs for Typical Summer and Winter Days

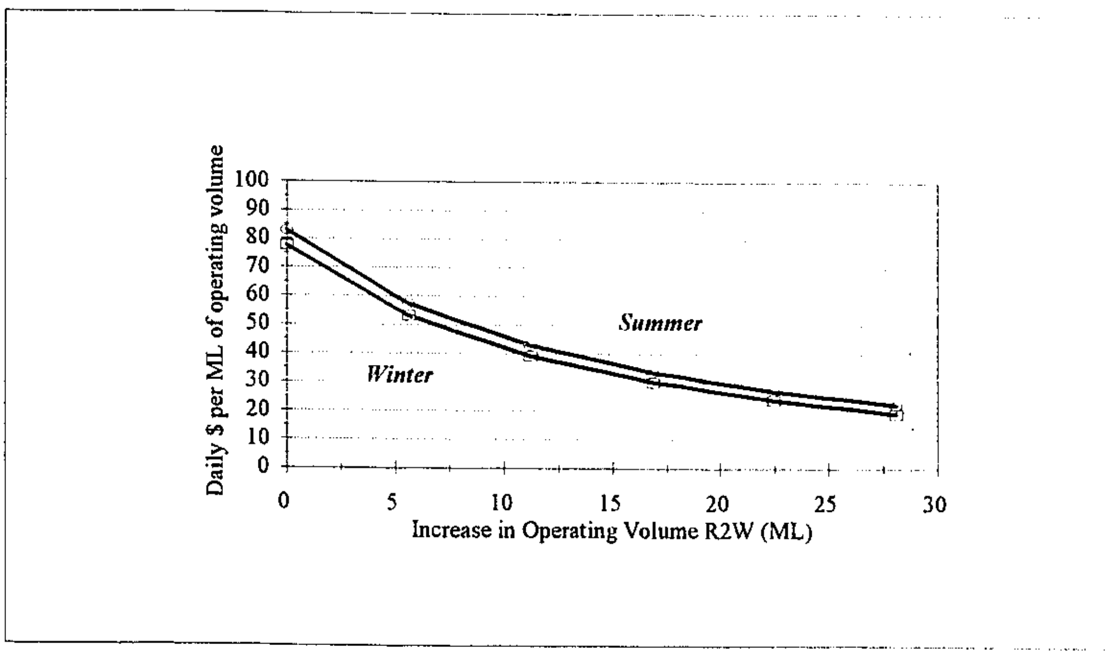

Figure 5.30 - Glen Cairn/Stittsville Branch Energy Costs per Unit Operating Volume for Typical Summer and Winter Days

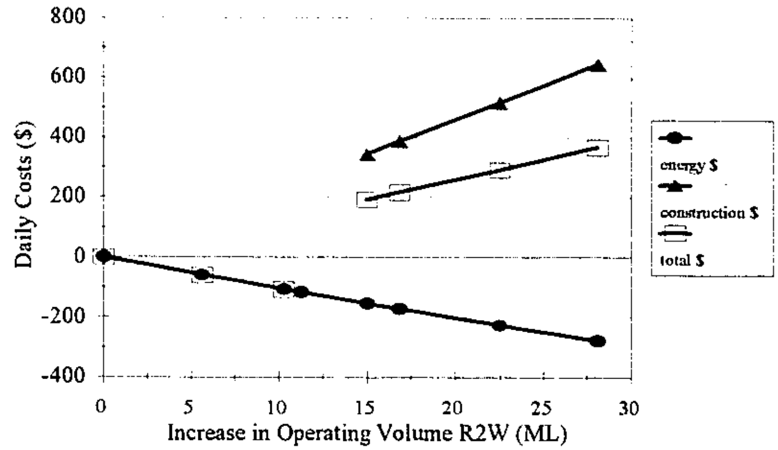

Figure 5.31 - Glen Cairn/Stittsville Branch Total Costs for a Typical Summer Day

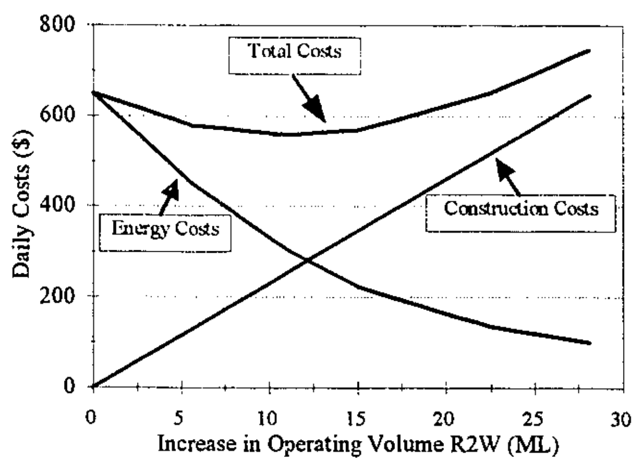

Figure 5.32 - Glen Cairn/Stittsville Branch Total Costs in an Hypothetical Case

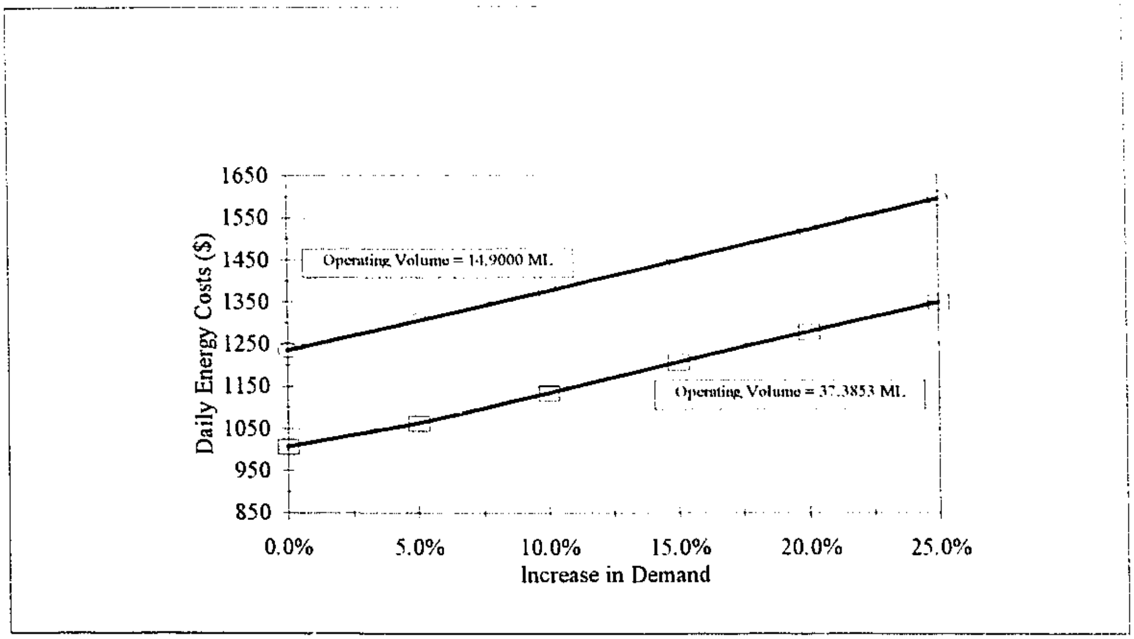

Figure 5.33 - Glen Cairn/Stittsville Branch Impact of Increasing Demand

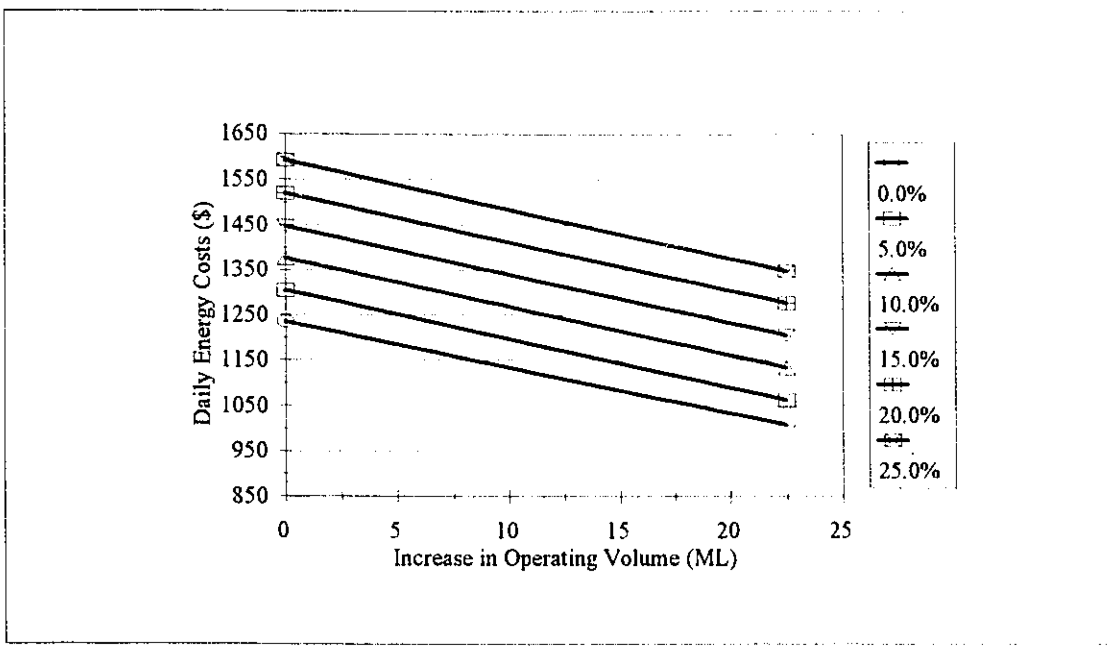

Figure 5.34 - Glen Cairn/Stittsville Increasing Demand with Increasing Operating Volume

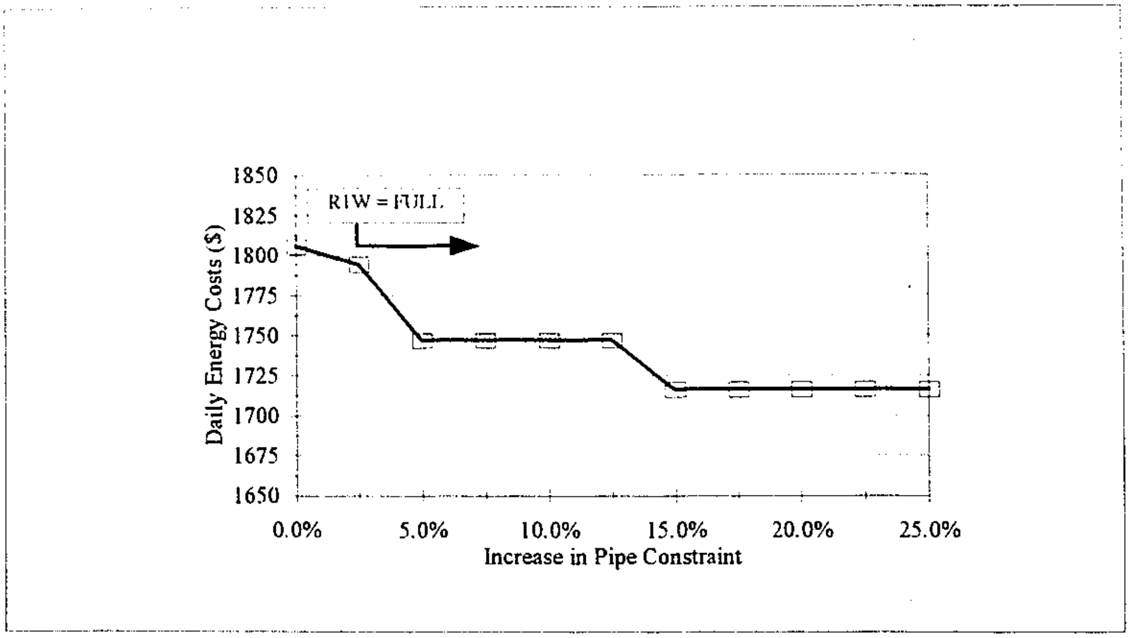

Figure 5.35 - Carlington Heights Branch: Impact of Increasing Pipe Constraint - Summer

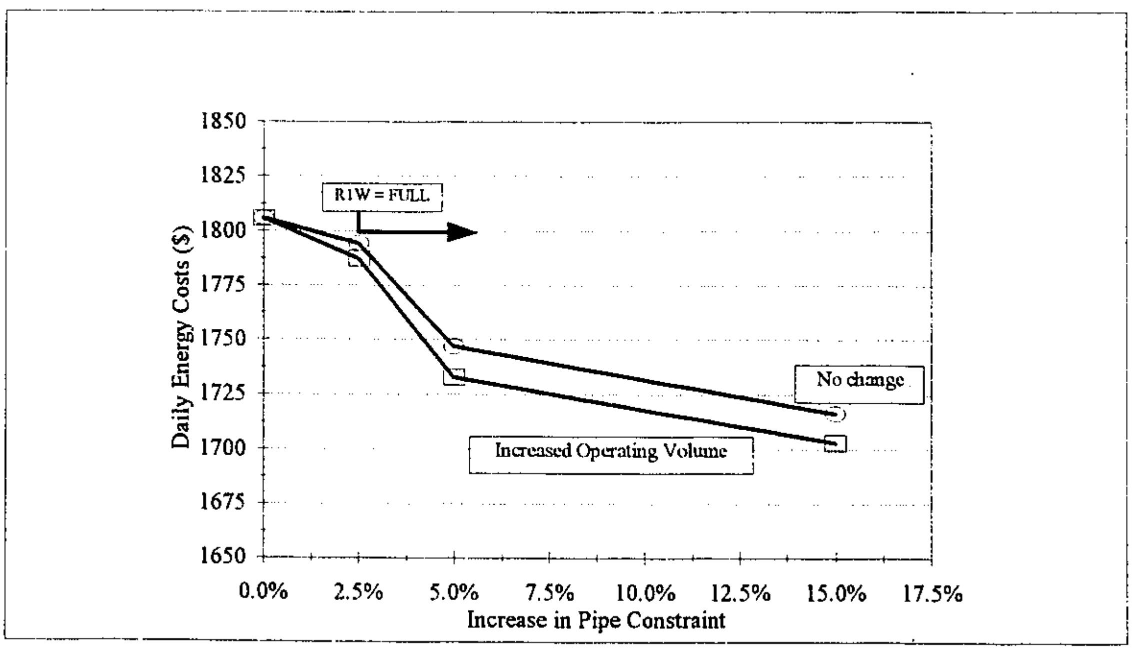

Figure 5.36 - Carlington Heights Branch: Impact of Increasing Hurdman Bridge R1E Reservoir Operating Volume and the Pipe Constraint - Summer

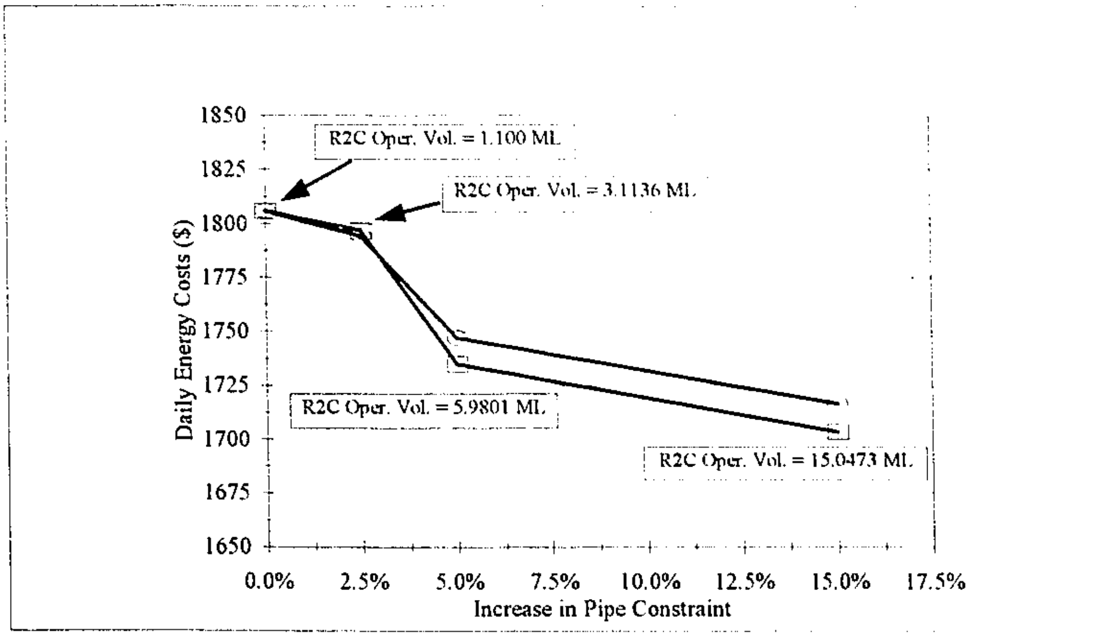

Figure 5.37 - Carlington Heights Branch: Impact of Increasing Billings Bridge R2C Reservoir Operating Volume and the Pipe Constraint - Summer

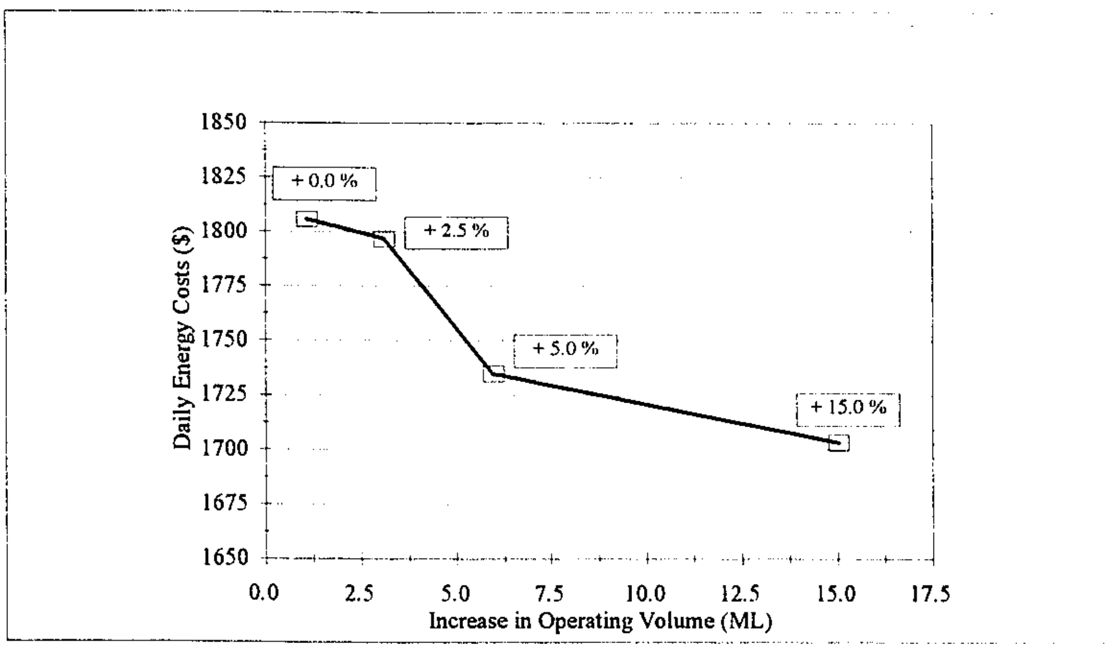

Figure 5.38 - Carlington Heights Branch: Impact of Increasing Billings Bridge R2C Reservoir Operating Volume - Summer

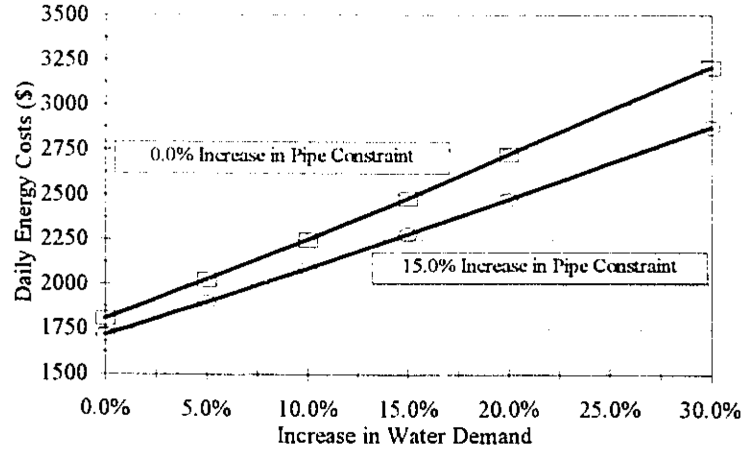

Figure 5.39 - Carlington Heights Branch: Impact of Increasing Water Demand - Summer

APPENDIX C

MODELS

HURDMAN BRIDGE BRANCH

Level I LP Formulation for "Optimizer"

Summer Night

Hurdman Bridge 1E	k = 1	Summer
Solution Cell	Night	
+D149	Minimize	0.0000
Variable Cells		
@COUNT(D150..D152)		
@COUNT(D150..D150)	>=	0.0000
@COUNT(D151..D151)	>=	0.0000
@COUNT(D152..D152)	>=	0.0000
@COUNT(C163..C163)	=	8.0000
@COUNT(C164..C164)	=	0.0000
@COUNT(C165..C165)	>=	51.9000
@COUNT(C166..C166)	<=	89.7000
@COUNT(C167..C167)	=	89.7000

Summer Day

Hurdman Bridge 1E	k = 2	Summer
Solution Cell	Day	
+D191	Minimize	0.0000
Variable Cells		
@COUNT(D192..D194)		
@COUNT(D192..D192)	>=	0.0000
@COUNT(D193..D193)	>=	0.0000
@COUNT(D194..D194)	>=	0.0000
@COUNT(C205..C205)	<=	16.0000
@COUNT(C206..C206)	=	0.0000
@COUNT(C207..C207)	>=	51.9000
@COUNT(C208..C208)	<=	89.7000
@COUNT(C209..C209)	=	51.9000

Winter Night

Hurdman Bridge 1E	k = 1	Winter
Solution Cell	Night	
+D243	Minimize	0.0000
Variable Cells		
@COUNT(D244..D246)		
@COUNT(D244..D244)	>=	0.0000
@COUNT(D245..D245)	>=	0.0000
@COUNT(D246..D246)	>=	0.0000
@COUNT(C259..C259)	=	8.0000
@COUNT(C260..C260)	=	0.0000
@COUNT(C261..C261)	>=	41.7000
@COUNT(C262..C262)	<=	89.7000
@COUNT(C263..C263)	=	83.0846

Winter Day

Hurdman Bridge 1E	k = 2	Winter
Solution Cell	Day	
+D286	Minimize	0.0000
Variable Cells		
@COUNT(D287..D289)		
@COUNT(D287..D287)	>=	0.0000
@COUNT(D288..D288)	>=	0.0000
@COUNT(D289..D289)	>=	0.0000
@COUNT(C300..C300)	<=	16.0000
@COUNT(C301..C301)	=	0.0000
@COUNT(C302..C302)	>=	41.7000
@COUNT(C303..C303)	<=	89.7000
@COUNT(C304..C304)	=	48.3154

BILLINGS BRIDGE BRANCH

Level I LP Formulation for "Optimizer"

Summer Night

Billings Bridge 2C	k = 1	Summer
Solution Cell	Night	
+D156	Minimize	0.0000
Variable Cells		
@COUNT(D157..D166)		
Constraints		
@COUNT(D157..D157)	>=	0.0000
@COUNT(D158..D158)	>=	0.0000
@COUNT(D159..D159)	>=	0.0000
@COUNT(D160..D160)	>=	0.0000
@COUNT(D161..D161)	>=	0.0000
@COUNT(D162..D162)	>=	0.0000
@COUNT(D163..D163)	>=	0.0000
@COUNT(D164..D164)	>=	0.0000
@COUNT(D165..D165)	>=	0.0000
@COUNT(D166..D166)	>=	0.0000
@COUNT(C177..C177)	=	6.0000
@COUNT(C178..C178)	=	0.0000
@COUNT(C179..C179)	>=	2.3000
@COUNT(C180..C180)	<=	3.4000
@COUNT(C181..C181)	=	3.4000

Summer Day

Billings Bridge 2C	k = 2	Summer
Solution Cell	Day	
+D214	Minimize	0.0000
Variable Cells		
@COUNT(D215..D224)		
Constraints		
@COUNT(D215..D215)	>=	0.0000
@COUNT(D216..D216)	>=	0.0000
@COUNT(D217..D217)	>=	0.0000
@COUNT(D218..D218)	>=	0.0000
@COUNT(D219..D219)	>=	0.0000
@COUNT(D220..D220)	>=	0.0000
@COUNT(D221..D221)	>=	0.0000
@COUNT(D222..D222)	>=	0.0000
@COUNT(D223..D223)	>=	0.0000
@COUNT(D224..D224)	>=	0.0000
@COUNT(C235..C235)	<=	18.0000
@COUNT(C236..C236)	=	0.0000
@COUNT(C237..C237)	>=	2.3000
@COUNT(C238..C238)	<=	3.4000
@COUNT(C239..C239)	=	2.3000

Level II LP Formulation for "Optimizer"

Summer Night

Solution Cell	Night	Summer
+E207	Equal	0.0000
Variable Cells		
@COUNT(B201..C206)		
Constraints		
@COUNT(B201..C206)	>=	0.0000
@COUNT(E201..E206)	>=	0.0000
@COUNT(D201..D206)	=	1.0000
@COUNT(B207..B207)	=	4.8000
@COUNT(C207..C207)	=	1.2000

Summer Day

Solution Cell	Day	Summer
+F289	Equal	0.0000
Variable Cells		
@COUNT(B271..D288)		
Constraints		
@COUNT(B271..D288)	>=	0.0000
@COUNT(F271..F288)	<=	0.0000
@COUNT(E271..E288)	<=	1.0000
@COUNT(B289)	=	3.0978
@COUNT(C289)	=	5.4662
@COUNT(D289)	=	8.7225

Level I LP Formulation for "Optimizer"

Winter Night

Billings Bridge 2C	k = 1	Winter
Solution Cell	Night	
+D301	Minimize	0.0000
Variable Cells		
@COUNT(D302..D311)		
Constraints		
@COUNT(D302..D302)	>=	0.0000
@COUNT(D303..D303)	>=	0.0000
@COUNT(D304..D304)	>=	0.0000
@COUNT(D305..D305)	>=	0.0000
@COUNT(D306..D306)	>=	0.0000
@COUNT(D307..D307)	>=	0.0000
@COUNT(D308..D308)	>=	0.0000
@COUNT(D309..D309)	>=	0.0000
@COUNT(D310..D310)	>=	0.0000
@COUNT(D311..D311)	>=	0.0000
@COUNT(C322..C322)	=	6.0000
@COUNT(C323..C323)	=	0.0000
@COUNT(C324..C324)	>=	2.5000
@COUNT(C325..C325)	<=	3.4000
@COUNT(C326..C326)	=	3.4000

Winter Day

Billings Bridge 2C	k = 2	Winter
Solution Cell	Day	
+D347	Minimize	0.0000
Variable Cells		
@COUNT(D348..D357)		
Constraints		
@COUNT(D348..D348)	>=	0.0000
@COUNT(D349..D349)	>=	0.0000
@COUNT(D350..D350)	>=	0.0000
@COUNT(D351..D351)	>=	0.0000
@COUNT(D352..D352)	>=	0.0000
@COUNT(D353..D353)	>=	0.0000
@COUNT(D354..D354)	>=	0.0000
@COUNT(D355..D355)	>=	0.0000
@COUNT(D356..D356)	>=	0.0000
@COUNT(D357..D357)	>=	0.0000
@COUNT(C368..C368)	<=	18.0000
@COUNT(C369..C369)	=	0.0000
@COUNT(C370..C370)	>=	2.5000
@COUNT(C371..C371)	<=	3.4000
@COUNT(C372..C372)	=	2.5000

Level II LP Formulation for "Optimizer"

Winter Night

Not necessary

Winter Day

Solution Cell	Day	Winter
+E422	Equal	0.0000
Variable Cells		
@COUNT(B404..C421)		
Constraints		
@COUNT(B404..C421)	>=	0.0000
@COUNT(E404..E421)	<=	0.0000
@COUNT(D404..D421)	<=	1.0000
@COUNT(B422)	=	3.4512
@COUNT(C422)	=	14.0880

CARLINGTON HEIGHTS BRANCH

Level I LP Formulation for "Optimizer"

Summer Night

Carlington Heights 1W	k = 1	Summer
Solution Cell	Night	
+D287	Minimize	0.0000
Variable Cells		
@COUNT(D288..D308)		
Constraints		
@COUNT(D288..D288)	>=	0.0000
@COUNT(D289..D289)	>=	0.0000
@COUNT(D290..D290)	>=	0.0000
@COUNT(D291..D291)	>=	0.0000
@COUNT(D292..D292)	>=	0.0000
@COUNT(D293..D293)	>=	0.0000
@COUNT(D294..D294)	>=	0.0000
@COUNT(D295..D295)	>=	0.0000
@COUNT(D296..D296)	>=	0.0000
@COUNT(D297..D297)	>=	0.0000
@COUNT(D298..D298)	>=	0.0000
@COUNT(D299..D299)	>=	0.0000
@COUNT(D300..D300)	>=	0.0000
@COUNT(D301..D301)	>=	0.0000
@COUNT(D302..D302)	>=	0.0000
@COUNT(D303..D303)	>=	0.0000
@COUNT(D304..D304)	>=	0.0000
@COUNT(D305..D305)	>=	0.0000
@COUNT(D306..D306)	>=	0.0000
@COUNT(D307..D307)	>=	0.0000
@COUNT(D308..D308)	>=	0.0000
@COUNT(C326..C326)	<=	8.0000
@COUNT(C327..C327)	<=	8.0000
@COUNT(C328..C328)	>=	8.0000
@COUNT(C329..C329)	=	0.0000
@COUNT(C330..C330)	>=	68.5000
@COUNT(C331..C331)	<=	109.1000
@COUNT(C332..C332)	=	106.5041

Summer Day

Carlington Heights 1W	k = 2	Summer
Solution Cell	Day	
+D370	Minimize	0.0000
Variable Cells		
@COUNT(D371..D391)		
Constraints		
@COUNT(D371..D371)	>=	0.0000
@COUNT(D372..D372)	>=	0.0000
@COUNT(D373..D373)	>=	0.0000
@COUNT(D374..D374)	>=	0.0000
@COUNT(D375..D375)	>=	0.0000
@COUNT(D376..D376)	>=	0.0000
@COUNT(D377..D377)	>=	0.0000
@COUNT(D378..D378)	>=	0.0000
@COUNT(D379..D379)	>=	0.0000
@COUNT(D380..D380)	>=	0.0000
@COUNT(D381..D381)	>=	0.0000
@COUNT(D382..D382)	>=	0.0000
@COUNT(D383..D383)	>=	0.0000
@COUNT(D384..D384)	>=	0.0000
@COUNT(D385..D385)	>=	0.0000
@COUNT(D386..D386)	>=	0.0000
@COUNT(D387..D387)	>=	0.0000
@COUNT(D388..D388)	>=	0.0000
@COUNT(D389..D389)	>=	0.0000
@COUNT(D390..D390)	>=	0.0000
@COUNT(D391..D391)	>=	0.0000
@COUNT(C411..C411)	<=	16.0000
@COUNT(C412..C412)	<=	16.0000
@COUNT(C413..C413)	=	0.0000
@COUNT(C414..C414)	>=	68.5000
@COUNT(C415..C415)	<=	109.1000
@COUNT(C416..C416)	=	68.5000

Level II LP Formulation for "Optimizer"

Summer Night

Solution Cell	Night	Summer
+E363	Equal	0.0000
Variable Cells		
@COUNT(B355..C362)		
Constraints		
@COUNT(B355..C362)	>=	0.0000
@COUNT(B355..C362)	<=	1.0000
@COUNT(E355..E362)	>=	0.0000
@COUNT(D355..D362)	>=	1.0000
@COUNT(B363..B363)	=	8.0000
@COUNT(C363..C363)	=	8.0000

Summer Day

Solution Cell	Day	Summer
+E462	Equal	0.0000
Variable Cells		
@COUNT(B446..C461)		
Constraints		
@COUNT(B446..C461)	>=	0.0000
@COUNT(B446..C461)	<=	1.0000
@COUNT(E446..E461)	<=	0.0000
@COUNT(B462..B462)	=	9.8428
@COUNT(C462..C462)	=	16.0000

Level I LP Formulation for "Optimizer"

Winter Night

Carlington Heights 1W	k = 1	Winter
Solution Cell	Night	
+D470	Minimize	0.0000
Variable Cells		
@COUNT(D471..D491)		
Constraints		
@COUNT(D471..D471)	>=	0.0000
@COUNT(D472..D472)	>=	0.0000
@COUNT(D473..D473)	>=	0.0000
@COUNT(D474..D474)	>=	0.0000
@COUNT(D475..D475)	>=	0.0000
@COUNT(D476..D476)	>=	0.0000
@COUNT(D477..D477)	>=	0.0000
@COUNT(D478..D478)	>=	0.0000
@COUNT(D479..D479)	>=	0.0000
@COUNT(D480..D480)	>=	0.0000
@COUNT(D481..D481)	>=	0.0000
@COUNT(D482..D482)	>=	0.0000
@COUNT(D483..D483)	>=	0.0000
@COUNT(D484..D484)	>=	0.0000
@COUNT(D485..D485)	>=	0.0000
@COUNT(D486..D486)	>=	0.0000
@COUNT(D487..D487)	>=	0.0000
@COUNT(D488..D488)	>=	0.0000
@COUNT(D489..D489)	>=	0.0000
@COUNT(D490..D490)	>=	0.0000
@COUNT(D491..D491)	>=	0.0000
@COUNT(C509..C509)	<=	8.0000
@COUNT(C510..C510)	<=	8.0000
@COUNT(C511..C511)	>=	8.0000
@COUNT(C512..C512)	=	0.0000
@COUNT(C513..C513)	>=	68.5000
@COUNT(C514..C514)	<=	109.1000
@COUNT(C515..C515)	=	101.9087

Winter Day

Carlington Heights 1W	k = 2	Winter
Solution Cell	Day	
+D553	Minimize	0.0000
Variable Cells		
@COUNT(D554..D574)		
Constraints		
@COUNT(D554..D554)	>=	0.0000
@COUNT(D555..D555)	>=	0.0000
@COUNT(D556..D556)	>=	0.0000
@COUNT(D557..D557)	>=	0.0000
@COUNT(D558..D558)	>=	0.0000
@COUNT(D559..D559)	>=	0.0000
@COUNT(D560..D560)	>=	0.0000
@COUNT(D561..D561)	>=	0.0000
@COUNT(D562..D562)	>=	0.0000
@COUNT(D563..D563)	>=	0.0000
@COUNT(D564..D564)	>=	0.0000
@COUNT(D565..D565)	>=	0.0000
@COUNT(D566..D566)	>=	0.0000
@COUNT(D567..D567)	>=	0.0000
@COUNT(D568..D568)	>=	0.0000
@COUNT(D569..D569)	>=	0.0000
@COUNT(D570..D570)	>=	0.0000
@COUNT(D571..D571)	>=	0.0000
@COUNT(D572..D572)	>=	0.0000
@COUNT(D573..D573)	>=	0.0000
@COUNT(D574..D574)	>=	0.0000
@COUNT(C592..C592)	<=	16.0000
@COUNT(C593..C593)	<=	16.0000
@COUNT(C594..C594)	=	0.0000
@COUNT(C595..C595)	>=	68.5000
@COUNT(C596..C596)	<=	109.1000
@COUNT(C597..C597)	=	68.5000

Level II LP Formulation for "Optimizer"

Winter Night

Not necessary

Winter Day

Solution Cell	Day	Winter
+H643	Equal	0.0000
Variable Cells		
@COUNT(B627..C642,E627		
Constraints		
@COUNT(B627..C642,E627	>=	0.0000
@COUNT(G627..G642)	>=	0.0000
@COUNT(G627..G642)	<=	1.0000
@COUNT(H627..H642)	<=	0.0000
@COUNT(B643..B643)	=	3.1030
@COUNT(C643..C643)	=	0.7715
@COUNT(D643..D643)	=	3.9615
@COUNT(E643..E643)	=	2.3928
@COUNT(F643..F643)	=	5.7712

GLEN CAIRN/STITTSVILLE BRANCH

Level I LP Formulation for "Optimizer"

Summer Night

GlenCairn 2W	k = 1	Summer
Solution Cell	Night	
+D212	Minimize	0.0000
Variable Cells		
@COUNT(D213..D224)		
Constraints		
@COUNT(D213..D213)	>=	0.0000
@COUNT(D214..D214)	>=	0.0000
@COUNT(D215..D215)	>=	0.0000
@COUNT(D216..D216)	>=	0.0000
@COUNT(D217..D217)	>=	0.0000
@COUNT(D218..D218)	>=	0.0000
@COUNT(D219..D219)	>=	0.0000
@COUNT(D220..D220)	>=	0.0000
@COUNT(D221..D221)	>=	0.0000
@COUNT(D222..D222)	>=	0.0000
@COUNT(D223..D223)	>=	0.0000
@COUNT(D224..D224)	>=	0.0000
@COUNT(C243..C243)	<=	8.0000
@COUNT(C244..C244)	<=	8.0000
@COUNT(C245..C245)	>=	8.0000
@COUNT(C246..C246)	=	0.0000
@COUNT(C247..C247)	>=	23.8000
@COUNT(C248..C248)	>=	6.8000
@COUNT(C249..C249)	<=	38.7000
@COUNT(C250..C250)	<=	19.5000
@COUNT(C251..C251)	=	38.7000
@COUNT(C252..C252)	=	19.5000

Summer Day

GlenCairn 2W	k = 2	Summer
Solution Cell	Day	
+D286	Minimize	0.0000
Variable Cells		
@COUNT(D287..D298)		
Constraints		
@COUNT(D287..D287)	>=	0.0000
@COUNT(D288..D288)	>=	0.0000
@COUNT(D289..D289)	>=	0.0000
@COUNT(D290..D290)	>=	0.0000
@COUNT(D291..D291)	>=	0.0000
@COUNT(D292..D292)	>=	0.0000
@COUNT(D293..D293)	>=	0.0000
@COUNT(D294..D294)	>=	0.0000
@COUNT(D295..D295)	>=	0.0000
@COUNT(D296..D296)	>=	0.0000
@COUNT(D297..D297)	>=	0.0000
@COUNT(D298..D298)	>=	0.0000
@COUNT(C317..C317)	<=	16.0000
@COUNT(C318..C318)	<=	16.0000
@COUNT(C319..C319)	=	0.0000
@COUNT(C320..C320)	>=	23.8000
@COUNT(C321..C321)	>=	6.8000
@COUNT(C322..C322)	<=	38.7000
@COUNT(C323..C323)	<=	19.5000
@COUNT(C324..C324)	=	23.8000
@COUNT(C325..C325)	=	6.8000

Level II LP Formulation for "Optimizer"

Summer Night

Solution Cell	Night	Summer
+E280	Equal	0.0000
Variable Cells		
@COUNT(B272..C279)		
Constraints		
@COUNT(B272..C279)	>=	0.0000
@COUNT(E272..E279)	>=	0.0000
@COUNT(D272..D279)	=	1.0000
@COUNT(B280..B280)	=	3.2429
@COUNT(C280..C280)	=	4.7571

Summer Day

Solution Cell	Day	Summer
+E371	Equal	0.0000
Variable Cells		
@COUNT(B355..C370)		
Constraints		
@COUNT(B355..C370)	>=	0.0000
@COUNT(B355..C370)	<=	1.0000
@COUNT(E355..E370)	<=	0.0000
@COUNT(B371..B371)	=	7.7566
@COUNT(C371..C371)	=	16.0000

Level I LP Formulation for "Optimizer"

Winter Night

GlenCairn 2W	k = 1	Winter
Solution Cell	Night	
+D379	Minimize	0.0000
Variable Cells		
@COUNT(D380..D391)		
Constraints		
@COUNT(D380..D380)	>=	0.0000
@COUNT(D381..D381)	>=	0.0000
@COUNT(D382..D382)	>=	0.0000
@COUNT(D383..D383)	>=	0.0000
@COUNT(D384..D384)	>=	0.0000
@COUNT(D385..D385)	>=	0.0000
@COUNT(D386..D386)	>=	0.0000
@COUNT(D387..D387)	>=	0.0000
@COUNT(D388..D388)	>=	0.0000
@COUNT(D389..D389)	>=	0.0000
@COUNT(D390..D390)	>=	0.0000
@COUNT(D391..D391)	>=	0.0000
@COUNT(C410..C410)	<=	8.0000
@COUNT(C411..C411)	<=	8.0000
@COUNT(C412..C412)	>=	8.0000
@COUNT(C413..C413)	=	0.0000
@COUNT(C414..C414)	>=	24.1000
@COUNT(C415..C415)	>=	6.8000
@COUNT(C416..C416)	<=	38.7000
@COUNT(C417..C417)	<=	19.5000
@COUNT(C418..C418)	=	38.7000
@COUNT(C419..C419)	=	19.5000

Winter Day

GlenCairn 2W	k = 2	Winter
Solution Cell	Day	
+D453	Minimize	0.0000
Variable Cells		
@COUNT(D454..D465)		
Constraints		
@COUNT(D454..D454)	>=	0.0000
@COUNT(D455..D455)	>=	0.0000
@COUNT(D456..D456)	>=	0.0000
@COUNT(D457..D457)	>=	0.0000
@COUNT(D458..D458)	>=	0.0000
@COUNT(D459..D459)	>=	0.0000
@COUNT(D460..D460)	>=	0.0000
@COUNT(D461..D461)	>=	0.0000
@COUNT(D462..D462)	>=	0.0000
@COUNT(D463..D463)	>=	0.0000
@COUNT(D464..D464)	>=	0.0000
@COUNT(D465..D465)	>=	0.0000
@COUNT(C484..C484)	<=	16.0000
@COUNT(C485..C485)	<=	16.0000
@COUNT(C486..C486)	=	0.0000
@COUNT(C487..C487)	>=	24.1000
@COUNT(C488..C488)	>=	6.8000
@COUNT(C489..C489)	<=	38.7000
@COUNT(C490..C490)	<=	19.5000
@COUNT(C491..C491)	=	24.1000
@COUNT(C492..C492)	=	6.8000

Level II LP Formulation for "Optimizer"

Winter Night

Solution Cell	Night	Winter
+F447	Equal	0.0000
Variable Cells		
@COUNT(B439..D446)		
Constraints		
@COUNT(B439..D446)	>=	0.0000
@COUNT(B439..D446)	<=	1.0000
@COUNT(F439..F446)	>=	0.0000
@COUNT(E439..E446)	>=	1.0000
@COUNT(E439..E446)	<=	2.0000
@COUNT(B447..B447)	=	7.1026

Winter Day

Solution Cell	Day	Winter
+E538	Equal	0.0000
Variable Cells		
@COUNT(B522..C537)		
Constraints		
@COUNT(B522..C537)	>=	0.0000
@COUNT(B522..C537)	<=	1.0000
@COUNT(D522..D537)	<=	2.0000
@COUNT(E522..E537)	<=	0.0000
@COUNT(B538..B538)	=	3.2292
@COUNT(C538..C538)	=	16.0000

BARRHAVEN SUB-BRANCH

Level I LP Formulation for "Optimizer"

Summer Night

Barrhaven	k = 1	Summer
Solution Cell	Night	
+D145	Minimize	0.0000
Variable Cells		
@COUNT(D146..D158)		
Constraints		
@COUNT(D146..D146)	>=	0.0000
@COUNT(D147..D147)	>=	0.0000
@COUNT(D148..D148)	>=	0.0000
@COUNT(D149..D149)	>=	0.0000
@COUNT(D150..D150)	>=	0.0000
@COUNT(D151..D151)	>=	0.0000
@COUNT(D152..D152)	>=	0.0000
@COUNT(D153..D153)	>=	0.0000
@COUNT(D154..D154)	>=	0.0000
@COUNT(D155..D155)	>=	0.0000
@COUNT(D156..D156)	>=	0.0000
@COUNT(D157..D157)	>=	0.0000
@COUNT(D158..D158)	>=	0.0000
@COUNT(C165..C165)	=	6.0000
@COUNT(C166..C166)	=	0.0000

Summer Day

Barrhaven	k = 2	Summer
Solution Cell	Day	
+D188	Minimize	0.0000
Variable Cells		
@COUNT(D189..D201)		
Constraints		
@COUNT(D189..D189)	>=	0.0000
@COUNT(D190..D190)	>=	0.0000
@COUNT(D191..D191)	>=	0.0000
@COUNT(D192..D192)	>=	0.0000
@COUNT(D193..D193)	>=	0.0000
@COUNT(D194..D194)	>=	0.0000
@COUNT(D195..D195)	>=	0.0000
@COUNT(D196..D196)	>=	0.0000
@COUNT(D197..D197)	>=	0.0000
@COUNT(D198..D198)	>=	0.0000
@COUNT(D199..D199)	>=	0.0000
@COUNT(D200..D200)	>=	0.0000
@COUNT(D201..D201)	>=	0.0000
@COUNT(C208..C208)	=	18.0000
@COUNT(C209..C209)	=	0.0000

Level II LP Formulation for "Optimizer"

Summer Night

Not necessary

Summer Day

Solution Cell	Day	Summer
+E259	Equal	0.0000
Variable Cells		
@COUNT(B241..C258)		
Constraints		
@COUNT(B241..C258)	>=	0.0000
@COUNT(E241..E258)	=	0.0000
@COUNT(D241..D258)	=	1.0000
@COUNT(B259)	=	2.7790
@COUNT(C259)	=	15.2211

Level I LP Formulation for "Optimizer"

Winter Night

Barrhaven	k = 1	Winter
Solution Cell	Night	
+D270	Minimize	0.0000
Variable Cells		
@COUNT(D271..D283)		
Constraints		
@COUNT(D271..D271)	>=	0.0000
@COUNT(D272 .D272)	>=	0.0000
@COUNT(D273..D273)	>=	0.0000
@COUNT(D274..D274)	>=	0.0000
@COUNT(D275..D275)	>=	0.0000
@COUNT(D276..D276)	>=	0.0000
@COUNT(D277..D277)	>=	0.0000
@COUNT(D278..D278)	>=	0.0000
@COUNT(D279..D279)	>=	0.0000
@COUNT(D280..D280)	>=	0.0000
@COUNT(D281..D281)	>=	0.0000
@COUNT(D282..D282)	>=	0.0000
@COUNT(D283..D283)	>=	0.0000
@COUNT(C290..C290)	=	6.0000
@COUNT(C291..C291)	=	0.0000

Winter Day

Barrhaven	k = 2	Winter
Solution Cell	Day	
+D313	Minimize	0.0000
Variable Cells		
@COUNT(D314..D326)		
Constraints		
@COUNT(D314..D314)	>=	0.0000
@COUNT(D315..D315)	>=	0.0000
@COUNT(D316..D316)	>=	0.0000
@COUNT(D317..D317)	>=	0.0000
@COUNT(D318..D318)	>=	0.0000
@COUNT(D319..D319)	>=	0.0000
@COUNT(D320..D320)	>=	0.0000
@COUNT(D321..D321)	>=	0.0000
@COUNT(D322..D322)	>=	0.0000
@COUNT(D323..D323)	>=	0.0000
@COUNT(D324..D324)	>=	0.0000
@COUNT(D325..D325)	>=	0.0000
@COUNT(D326..D326)	>=	0.0000
@COUNT(C333..C333)	=	18.0000
@COUNT(C334..C334)	=	0.0000

Level II LP Formulation for "Optimizer"

Winter Night

Not necessary

Winter Day

Solution Cell	Day	Winter
+E384	Equal	0.0000
Variable Cells		
@COUNT(B366..C383)		
Constraints		
@COUNT(B366..C383)	>=	0.0000
@COUNT(E366..E383)	=	0.0000
@COUNT(D366..D383)	=	1.0000
@COUNT(B384)	=	1.6485
@COUNT(C384)	=	16.3516

APPENDIX D

OTTAWA HYDRO RATES
AND
WPPS' BILLS

OTTAWA HYDRO

1994 COMMERCIAL RATES

(There was no rate increase for 1994)

GENERAL SERVICE (less than 2000 kW):

DEMAND		
1'ST kW	50	N/C
NEXT kW	4950	$5.05
ALL ADD'N		$13.20

CONSUMPTION		
1'ST kW.h	250	$0.0803
NEXT kW.h	12250	$0.0765
NEXT kW.h	1983900	$0.0562
ALL ADD'N		$0.0358

GENERAL SERVICE TIME-OF-USE (2000 – 5000kW):

		WINTER		SUMMER	
		On-Peak*	Off-Peak	On-Peak*	Off-Peak
DEMAND					
1ST kW	50	N/C	N/C	N/C	N/C
NEXT kW	4950	$5.40	N/C	$4.20	N/C
ALL ADDN		$15.25	N/C	$11.14	N/C
CONSUMPTION					
1ST kW.h	250	$0.1261	$0.0345	$0.1040	$0.0237
NEXT kW.h	6625	$0.1256	$0.0345	$0.1019	$0.0237
NEXT kW.h	1184000	$0.0863	$0.0345	$0.0713	$0.0237
ALL ADDN		$0.0469	$0.0345	$0.0406	$0.0237

LARGE USER TIME-OF-USE (over 5000kW):

6 6

WINTER *(October to March)*

On-Peak*	$15.50 for all kW
	$0.0469 for all kWh
Off-Peak	$0.0345 for all kWh

SUMMER *(April to September)*

On-Peak*	$11.32 for all kW
	$0.0406 for all kWh
Off-Peak	$0.0237 for all kWh

GENERAL SERVICE RESTRICTED HOUR:

*Outside Restricted Hours **.... 1/3 off the following rates:*

DEMAND	
0-5000 kW	$5.05
All Add'n	$13.20

CONSUMPTION	
All kWh	$0.0562

GENERAL SERVICE T.O.U. RESTRICTED HOUR (2000 – 5000kW):

*Outside Restricted Hours **.... 1/3 off the following rates:*

		WINTER		SUMMER	
		On-Peak*	Off-Peak	On-Peak*	Off-Peak
DEMAND	0-5000 kW	$5.40	N/C	$4.20	N/C
	All Add'n	$15.25	N/C	$11.14	N/C
CONSUMPTION	All kWh	$0.0863	$0.0345	$0.0713	$0.0237

LARGE USER T.O.U. RESTRICTED (over 5000 kW):

*Outside Restricted Hours **..... 1/3 off the Large User rates above.*

RESTRICTED PENALTY

For ALL Restricted Accounts, during restricted hours.

WINTER *(October to March)*
$18.39 for all kW
$0.0440 for all kWh

SUMMER *(April to September)*
$13.43 for all kW
$0.0384 for all kWh

Notes:

* "On-Peak" Time is defined as weekdays from 7:00 a.m to 11:00 p.m, except for statutory holidays. All other times are considered "Off-Peak" hours.

** Restricted hours are those defined on the accompanying "Schedule of Restricted Hours". Statutory holidays are those defined on the "Schedule of Statutory Holidays".

HYDRO RATES

1994

UTILITY	1ST BLOCK cents/kWh	2ND BLOCK cents/kWh	3RD BLOCK cents/Kwh	BALANCE cents/Kwh	DEMAND OVER 50kw $/kW
OTTAWA	0- 250 8.03	250- 12,250 7.65	1,983,900 5.62	3.58	5.05
KANATA	250 11.80	12,250 8.00	1,632,800 5.79	3.58	5.50
GLOUCESTER	250 11.08	12,250 7.57	2,004,600 5.58	3.58	4.95
NEPEAN	250 10.20	12,250 7.49	2,129,000 5.54	3.58	4.85
GOULBOURN	250 13.43	12,250 8.42	-	6.00	6.05
ONTARIO	250 22.60	12,250 8.65	1,130,000 6.08	3.58	6.45

Ottawa Hydro
3025 Albion Road / Chemin Albion
P.O. Box 8700 / C.P. 8700
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(613) 738-6413

SERVICE FOR / SERVICE POUR	ACCOUNT NUMBER / NUMÉRO DE COMPTE
[redacted] P/R-0000 LEMIEUX ISLE	49-347171-9

GST # R119321529

2SH

DUE DATE: / DATE D'ÉCHÉANCE: AUG 16 93

AMOUNT ON OR BEFORE DUE DATE: / SI PAYÉ AVANT OU À DATE D'ÉCHÉ: 36,460.17

REG MUN OTTAWA CARLETON
FINANCIAL SERV SUPERVISOR
951 CLYDE, OTTAWA
K1Z 5A6

5 7 7 3 38,283.18

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Ottawa Hydro
3025 Albion Road / Chemin Albion
P.O. Box 8700 / C.P. 8700
Ottawa, Ontario K1G 3S4
(613) 738-6413

2SH

BILLING DATE / DATE DE FACTURATION	SERVICE FROM / SERVICE DU	SERVICE TO / SERVICE AU	DUE DATE / DATE D'ÉCHÉANCE
AUG 03 93	JUN 30 93	JUL 31 93	AUG 16 93

SERVICE FOR / SERVICE POUR	ACCOUNT NUMBER / NUMÉRO DE COMPTE	kW.h READING / RELEVÉ kW.h	kW.h CONSUMPTION / CONSOMMATION EN kW.h	NO. OF DAYS / NO. DE JOURS	AVG. kW.h/DAY / MOY. kW.h/JOUR
P/R-0000 LEMIEUX ISLE	49-347171-9			31	

DESCRIPTION		AMOUNT / MONTANT
BROUGHT FORWARD/A REPORTER		.00
PREVIOUS BILLING/FACTURE PRECEDENTE	JUN 30	25,711.39
PAYMENT(S) RECEIVED/PAIEMENT RECU	JUL 19	25,711.39CR
SUB-TOTAL/SOUS-TOTAL		.00
ENERGY CHARGES/CHARGES D'ENERGIE		48,368.02
DEMAND CHARGES/CHARGES DE DEMANDE		8,831.76
PEAK DATE/DATE GROS USAGE	93/07/07	
PEAK TIME/HEURE GROS USAGE	22:40	
POWER FACTOR/FACTEUR PUISS.	95.55% KW 2152.80 KVA 2253.14	
SUMMER PURCHASES/ACHATS ETE		
PEAK KWH/KWH PLUS GROS	481,106	
OFF PEAK KWH/KWH ORDINAIRE	584,568	
DEMAND KW/KW DEMANDE	2,152.80	
TRANSFORMER CREDIT/CREDIT DE TRANSFORMATEUR		1,291.68CR
TRANSFORMER LOSS/PERTE DE TRANSFORMATEUR		572.00CR
RESTRICTED HOUR DISCOUNT/RABAIS D'ENERGIE		18,875.93CR
GST EXEMPTION NUMBER GOVERNMENT		.00

signed — 1065,674

EQUAL PAYMENT INFORMATION / PAIEMENT MENSUEL

GST # R119321529

BILLED TO DATE / FACTURES À CE JOUR	PAYMENT TO DATE / PAIEMENT À CE JOUR	BALANCE / SOLDE
$	$	$

38,283.18

AMOUNT ON OR BEFORE DUE DATE: / SI PAYÉ AVANT OU À DATE D'ÉCHÉ: 36,460.17

290.55
36,750.72

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SERVICE POUR	NUMERO DE COMPTE (ACCOUNT NUMBER)
P/R-0000 BRITANNIA PSTN	49-349194-9

GST # R119321529

2SH

DUE DATE / DATE D'ECHEANCE: AUG 16 93

AMOUNT ON OR BEFORE DUE DATE / SI PAYE AVANT OU A DATE D'ECH: 63,852.29

REG MUN OTTAWA CARLETON
FINANCIAL SERV SUPERVISOR
951 CLYDE, OTTAWA
K1Z 5A6

2 7 5 0

67,044.90

<49349194929308167000063852295000067044900>

⑆0006⑈002⑆ 0019⑈10⑈96 JULY

Ottawa Hydro

3025 Albion Road / Chemin Albion
P.O. Box 8700 / C.P. 8700
Ottawa, Ontario K1G 3S4
(613) 738-6413

2SH

BILLING DATE / DATE DE FACTURATION	SERVICE FROM / SERVICE DU	SERVICE TO / SERVICE AU	DUE DATE / DATE D'ECHEANCE
AUG 03 93	JUN 30 93	JUL 31 93	AUG 16 93

SERVICE FOR / SERVICE POUR	ACCOUNT NUMBER / NUMÉRO DE COMPTE	kW.h READING / RELEVÉ kW.h	kW.h CONSUMPTION / CONSOMMATION EN kW.h	NO. OF DAYS / NO. DE JOURS	AVG. kW.h/DAY / MOY. kW.h/JOUR
P/R-0000 BRITANNIA PSTN	49-349194-9			31	

DESCRIPTION		AMOUNT / MONTANT
BROUGHT FORWARD/A REPORTER		.00
PREVIOUS BILLING/FACTURE PRECEDENTE	JUN 30	52,330.40
PAYMENT(S) RECEIVED/PAIEMENT RECU	JUL 19	52,330.40CR
SUB-TOTAL/SOUS-TOTAL		.00
ENERGY CHARGES/CHARGES D'ENERGIE		85,061.17
DEMAND CHARGES/CHARGES DE DEMANDE		14,970.48
PEAK DATE/DATE GROS USAGE	93/07/09	
PEAK TIME/HEURE GROS USAGE	17:50	
POWER FACTOR/FACTEUR PUISS.	92.77% KW 3614.40 KVA 3896.24	
SUMMER PURCHASES/ACHATS ETE		
PEAK KWH/KWH PLUS GROS	823,237	
OFF PEAK KWH/KWH ORDINAIRE	1,103,522	
DEMAND KW/KW DEMANDE	3,614.40	
TRANSFORMER CREDIT/CREDIT DE TRANSFORMATEUR		2,168.64CR
TRANSFORMER LOSS/PERTE DE TRANSFORMATEUR		1,000.26CR
RESTRICTED HOUR DISCOUNT/RABAIS D'ENERGIE		33,010.46CR
GST EXEMPTION NUMBER GOVERNMENT		.00

1,926,759
237

EQUAL PAYMENT INFORMATION / PAIEMENT MENSUEL

GST # R119321529

BILLED TO DATE / FACTURES À CE JOUR	PAYMENT TO DATE / PAIEMENT À CE JOUR	BALANCE / SOLDE
$	$	$

AMOUNT AFTER DUE DATE: 67,044.90

AMOUNT ON OR BEFORE DUE DATE / SI PAYE AVANT OU A DATE D'ECH.: 63,852.29

387.00

RETAIN THIS PORTION FOR YOUR RECORDS

NOV 25 '94 09:08 FROM ENV E ... LEMIEUX ISLAND

Ottawa Hydro

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P.O. Box 8700 / C.P. 8700
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(613) 738-6413
GST # R119321529

SERVICE FOR / SERVICE POUR	ACCOUNT NUMBER / NUMERO DE COMPTE
P/R-0000 LEMIEUX ISLE	49-347171-9

AMOUNT ON OR BEFORE DUE DATE / SI PAYE AVANT OU A DATE D'ECH. 32,411.63CR

32,411.63CR

REG MUN OTTAWA CARLETON
ENVIRONMENTAL SERVICE DEPT
2FLR-111 LISGAR ST. OTTAWA
K2P 2L7

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Ottawa Hydro

3025 Albion Road / Chemin Albion
P.O. Box 8700 / C.P. 8700
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(613) 738-6413
GST # R119321529

BILLING DATE / DATE DE FACTURATION	SERVICE FROM / SERVICE DU	SERVICE TO / SERVICE AU	DUE DATE / DATE D'ECHEANCE
FEB 01 93	DEC 31 92	JAN 31 93	

SERVICE FOR / SERVICE POUR	ACCOUNT NUMBER / NUMERO DE COMPTE	KWH READING / RELEVE KWH	KWH CONSUMPTION / CONSOMMATION EN KWH	NO. OF DAYS / NO DE JOURS	AVG KWH/DAY / MOY KWH/JOUR
P/R-0000 LEMIEUX ISLE	49-347171-9				

DESCRIPTION	AMOUNT/MONTANT
BROUGHT FORWARD/A REPORTER	68,144.58CR
PREVIOUS BILLING/FACTURE PRECEDENTE DEC 31	51,768.10
PAYMENT(S) RECEIVED/PAIEMENT RECU JAN 18	51,768.10CR
SUB-TOTAL/SOUS-TOTAL	68,144.58CR
ENERGY CHARGES/CHARGES D'ENERGIE	44,936.80
DEMAND CHARGES/CHARGES DE DEMANDE	11,121.84
PEAK DATE/DATE GROS USAGE 93/01/06	
PEAK TIME/HEURE GROS USAGE 11:55	
POWER FACTOR/FACTEUR PUISS. 93.08% KW 2109.60 KVA 2266.36	
WINTER PURCHASES/ACHATS HIVER	
PEAK KWH/KWH PLUS GROS 331,648	
OFF PEAK KWH/ KWH ORDINAIRE 465,080	
DEMAND KW/KW DEMANDE 2,109.60	
TRANSFORMER CREDIT/CREDIT DE TRANSFORMATEUR	1,265.76CR
TRANSFORMER LOSS/PERTE DE TRANSFORMATEUR	560.57CR
RESTRICTED HOUR DISCOUNT/RABAIS D'ENERGIE	18,499.36CR
GST EXEMPTION NUMBER GOVERNMENT	.00

-23 207.70

796,728

TRANSPORTATION DEPARTMENT
Rec'd. FEB 3 1993
FILE NO.
RECORD NO.
FILE / CATEGORY
TO

EQUAL PAYMENT INFORMATION / PAIEMENT MENSUEL

BILLED TO DATE / FACTURES A CE JOUR	PAYMENT TO DATE / PAIEMENT A CE JOUR	BALANCE / SOLDE
$	$	$

AMOUNT AFTER DUE DATE / SI PAYE APRES DATE D'ECH.: 32,411.63CR

AMOUNT ON OR BEFORE DUE DATE / SI PAYE AVANT OU A DATE D'ECH.: 32,411.63CR

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23 275 CR

Ottawa Hydro
(613) 738-6413
GST # R119321529

SERVICE FOR / SERVICE POUR	ACCOUNT NUMBER / NUMERO DE COMPTE
P/R-0000 BRITANNIA PSTN	49-349194-9

FEB 16 93

19,606.10

20,586.41

REG MUN OTTAWA CARLETON
ENVIRONMENTAL SERVICE DEPT
2FLR-111 LISGAR ST. OTTAWA
K2P 2L7

Ottawa Hydro
3025 Albion Road / Chemin Albion
P.O. Box 8700 / C.P. 8700
Ottawa, Ontario K1G 3S4
(613) 738-6413
GST # R119321529

BILLING DATE / DATE DE FACTURATION	SERVICE FROM / SERVICE DU	SERVICE TO / SERVICE AU	DUE DATE / DATE D'ECHEANCE
FEB 01 93	DEC 31 92	JAN 31 93	FEB 16 93

SERVICE FOR / SERVICE POUR	ACCOUNT NUMBER / NUMERO DE COMPTE
P/R-0000 BRITANNIA PSTN	49-349194-9

DESCRIPTION	AMOUNT / MONTANT
BROUGHT FORWARD/A REPORTER	43,668.22CR
PREVIOUS BILLING/FACTURE PRECEDENTE DEC 31	57,509.63
PAYMENT(S) RECEIVED/PAIEMENT RECU JAN 18	57,509.63CR
SUB-TOTAL/SOUS-TOTAL	43,668.22CR
ENERGY CHARGES/CHARGES D'ENERGIE	80,410.12
DEMAND CHARGES/CHARGES DE DEMANDE	18,644.36
PEAK DATE/DATE GROS USAGE 93/01/28	
PEAK TIME/HEURE GROS USAGE 22:45	
POWER FACTOR/FACTEUR PUISS. 87.69% KW 3412.80 KVA 3891.84	
WINTER PURCHASES/ACHATS HIVER	
PEAK KWH/KWH PLUS GROS 606,063	
OFF PEAK KWH/ KWH ORDINAIRE 806,857 — 1,412,920	
DEMAND KW/KW DEMANDE 3,502.66	
TRANSFORMER CREDIT/CREDIT DE TRANSFORMATEUR	2,101.60CR
TRANSFORMER LOSS/PERTE DE TRANSFORMATEUR	990.60CR
RESTRICTED HOUR DISCOUNT/RABAIS D'ENERGIE	32,687.96CR
GST EXEMPTION NUMBER GOVERNMENT	.00

OTTAWA CARLETON TRANSPORTATION DEPARTMENT
Rec'd. FEB 3 1993
FILE NO.
RECORD NO.

EQUAL PAYMENT INFORMATION / PAIEMENT MENSUEL

BILLED TO DATE / FACTURES A CE JOUR	PAYMENT TO DATE / PAIEMENT A CE JOUR	BALANCE / SOLDE
$	$	$

169,223.41

AMOUNT AFTER DUE DATE / SI PAYE APRES DATE D'ECH.: 20,586.41

AMOUNT ON OR BEFORE DUE DATE / SI PAYE AVANT OU A DATE D'ECH.: 19,606.10

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25,166.00

CHAPTER 10

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