

Modeling as a Tool for Economic Analysis of Basement Flood Relief Projects

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The City of Winnipeg, with a population of 630,000, is centrally located in the southern part of the Province of Manitoba, Canada. Combined sewer systems service approximately 50% of the City of Winnipeg. These systems were installed from the early 1900s up until 1960 and primarily service the older core areas of the City. The original designs reflected the site conditions at the time; however, changes in land use and new development have resulted in dramatic increases in the volume and rate of stormwater runoff. The increased stormwater results in frequent sewer surcharge and backup into basements with associated property damages.

The City of Winnipeg has been carrying out an extensive basement flood relief program since 1977. The program is designed to upgrade basement flood protection to a minimum five-year level. The development and prioritization of proposed relief works is dependent on a comparison of the benefits of installing relief works to the implementation costs. SWMM modelling is used extensively in the program to develop relief options and to provide data for the economic analysis.

This chapter details the full development of a basement flood relief plan for the Dumoulin Combined Sewer District in the City of Winnipeg. It includes descriptions of model development, calibration and verification, assessment of existing levels of basement flood protection and relief alternatives to upgrade the combined sewer system, and the economic analysis of proposed relief works.

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5.1 Introduction

The Dumoulin District covers approximately 62 ha (153.2 acres) and is centrally located within the City of Winnipeg (see Figure 5.1). The district comprises primarily single-family residences developed between the early 1900s and 1960, with commercial sectors primarily along major thoroughfares, as well as interspersed throughout the area.

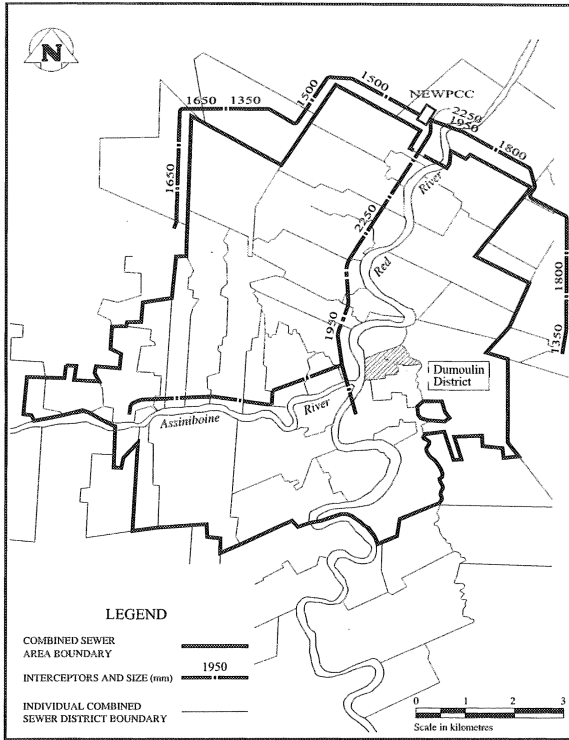


Figure 5.1 City of Winnipeg, showing the study area.

At present, the District is served by a combined sewer system and has a high incidence of basement flooding from intense summer storm events. The combined sewers in the Dumoulin District were mainly constructed in the period from 1902 to 1916 (Wardrop, 1963). The dry weather flow (DWF) from the district is diverted by a weir to a wastewater pumping station and pumped across the river to the City's interceptor sewer system (Wardrop, 1995). Flows

in excess of pumping station capacity of 136 L/s (2,155 gpm) overflow to the Red River.

The overall system inadequacies relate to the era in which the sewer system was designed. The level of protection provided by Winnipeg's combined sewer system depends largely on the time it was designed, with areas constructed prior to 1946 having a relatively low level of protection. The Dumoulin combined sewer system was designed using the rational method runoff calculation, with an intensity/duration formula equivalent to the current 2-y design storm. The 5-y design storm is currently used for drainage design in the City.

An additional time-related cause of flooding is a change of land use since the design period. Changes in land use such as replacement of single family units by apartment complexes, increased commercial uses with accompanying paved parking lots, paved back lanes, paved driveways, and street widening have a major impact on runoff. These changes reduce surface storage, increase imperviousness, and therefore reduce infiltration and increase the speed with which the runoff reaches the sewer.

5.2 Model Development

The first step in model development was the collection of all relevant physical data. The existing data base included such items as as-built construction drawings and overall plans of the sewer system, land use and zoning plans, rainfall data, aerial photos, and flow level monitoring data. These data were supplemented by a detailed district walkthrough inspection and field surveys to check and confirm surface characteristics, connected downspouts, sewer sizes, and critical manhole inverts.

The detailed District walkthrough inspection was designed to identify topographic details essential to the hydrologic modeling. This included key drainage items such as street high and low-points, lot grading and public lane drainage patterns that were required for subcatchment discretization. It also included details such as approximate size and location of impervious areas, ground slope and depressed areas in suitable detail for the initial estimation of these runoff related parameters for each subcatchment area. The survey also identified the location of all hydraulically connected downspouts so that these critical features could be modeled accurately. This information was transcribed onto hard copy aerial photographs and then transferred onto a digital map of the district.

Individual subcatchment boundaries were determined for each street drainage inlet, public lane or parking lot inlet on the basis of the survey information. The boundaries were then digitized and used to calculate subcatchment areas and estimate subcatchment width and percent imperviousness. Estimates for ground slope were initially made based on the visual observations of lot and street grades. The remainder of the runoff parameters were initially set to values previously used in basement flood relief studies in adjacent sewer districts (Steiss and Watters, 2001).

XP-SWMM version 7.2 was used to model the Dumoulin Combined Sewer System. The combined contributing area was discretized into 124 individual drainage areas, or subcatchments. The total combined sewer (CS) contributing area comprised 46.7 ha (115.4 acres) at an overall 35% imperviousness. Coincident with the subcatchment discretization task, the existing sewer systems were reviewed to select conduits and nodes for detailed modeling in the hydraulic flow routing module.

The sewer model consisted of 61 conduits, ranging in size from 300 to 1050 mm (12 - 42 in.) in diameter, and 59 nodes. This included every combined sewer pipe, with the exception of the piping in the separate stormwater area in the district. The original combined sewer system was installed in the Dumoulin District from 1902 to 1907. The combined trunk system was upgraded in 1960

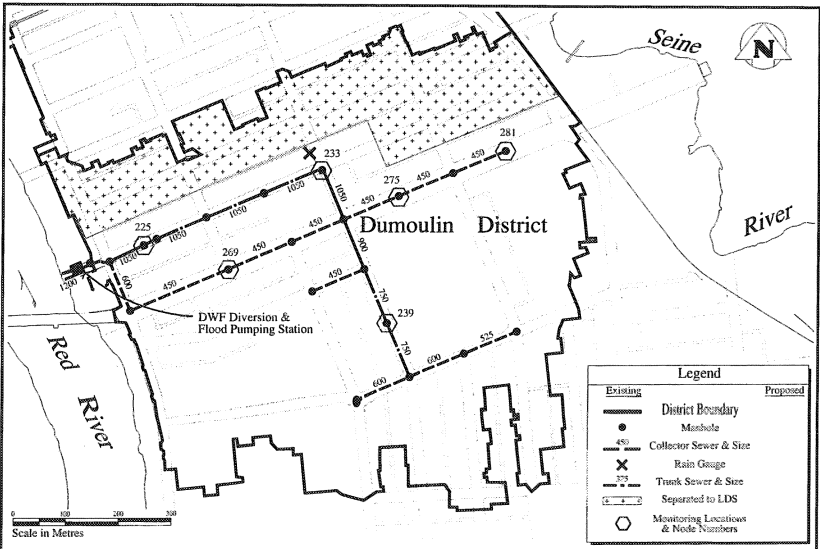


Figure 5.2 Combined sewer trunk and collector system, Dumoulin District.

to alleviate flooding problems in the district. The combined sewer trunk and collector system is shown on Figure 5.2.

A land drainage sewer (LDS) system was installed in the early 1970s to service a portion of the Dumoulin District. The land drainage works separated approximately 15 ha (37 acres) of drainage area from the combined sewer system. The separated area is also shown on Figure 5.2.

The district model was then used for the following analyses:

- model calibration and verification to sewer flow monitoring and rainfall data;
- hydraulic performance assessment of current levels of basement flood protection in the districts;
- development of hydraulic relief alternatives to upgrade the level of basement flood protection to the 5-y and 10-y levels; and
- economic analysis of hydraulic relief alternatives.

5.3 Model Calibration

Model calibration entailed the adjustment of selected model parameters such that model results matched measured data from a sewer monitoring program. The City's 2000 monitoring program consisted of continuous level monitoring at six locations in the Dumoulin trunk and major collector sewer system. Rainfall data were obtained from the City's continuous recording rain gauge network. The location of the nearest rain gauge and sewer monitoring locations within the Dumoulin District are shown on Figure 5.2.

There were several significant rainfall events during the 2000 monitoring season. Rainfall ranged from short duration, high intensity to longer duration events with a more uniform intensity. The recorded significant rainfall events considered for model calibration and verification are shown on Figure 5.3. A five-year design event is also shown for comparison.

The August 8 and 12 rainfall events were used for model calibration. The August 8 event consisted of 9.8 mm (0.39 in.) of rainfall over a 3.5-h duration. The August 12 rainfall consisted of 10.5 mm (0.41 in) over a one-hour period. The selection of these two events allowed the calibration exercise to consider events of varying intensity.

The calibration task initially started with calculated values for the easily measured model input parameters and typical values for the harder to quantify values. The model calibration entailed the adjustment of values for the following input parameters:

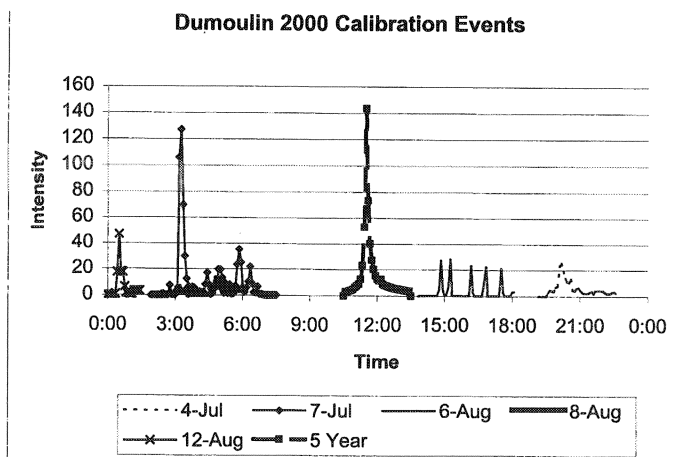


Figure 5.3 Significant rainfall events used for model calibration and verification.

- Subcatchment width - to alter the timing and shape of the flow hydrograph to match measured values.
- Percent impervious - to match hydrograph shape, particularly for smaller events where no runoff from pervious areas would be expected.
- Impervious area with zero detention storage - to match flows at start of event.
- Manning's n for impervious area - to adjust timing.
- Impervious area detention storage - to modify volume and rate of runoff from impervious areas.
- Manning's n for pipe roughness - to match flow conditions in the pipe network.

Figure 5.4 shows the August 12, 2000, rainfall hyetograph as well as the computed stage hydrographs at two monitoring locations. The locations are on the 750 mm (30 in.) combined trunk sewer (Node 239) and on a 450 mm (18 in.) collector sewer (Node 269). The model results closely match the peak monitored levels and generally follow the same shape of the hydrograph.

Similar results were obtained from the August 8, 2000, simulation. This analysis indicated that the model provided excellent correlation to the two calibration events. The model was then tested, without further adjustment, with additional storm events to verify the model parameter values. The following three storm events were used for the XPSWMM model verification:

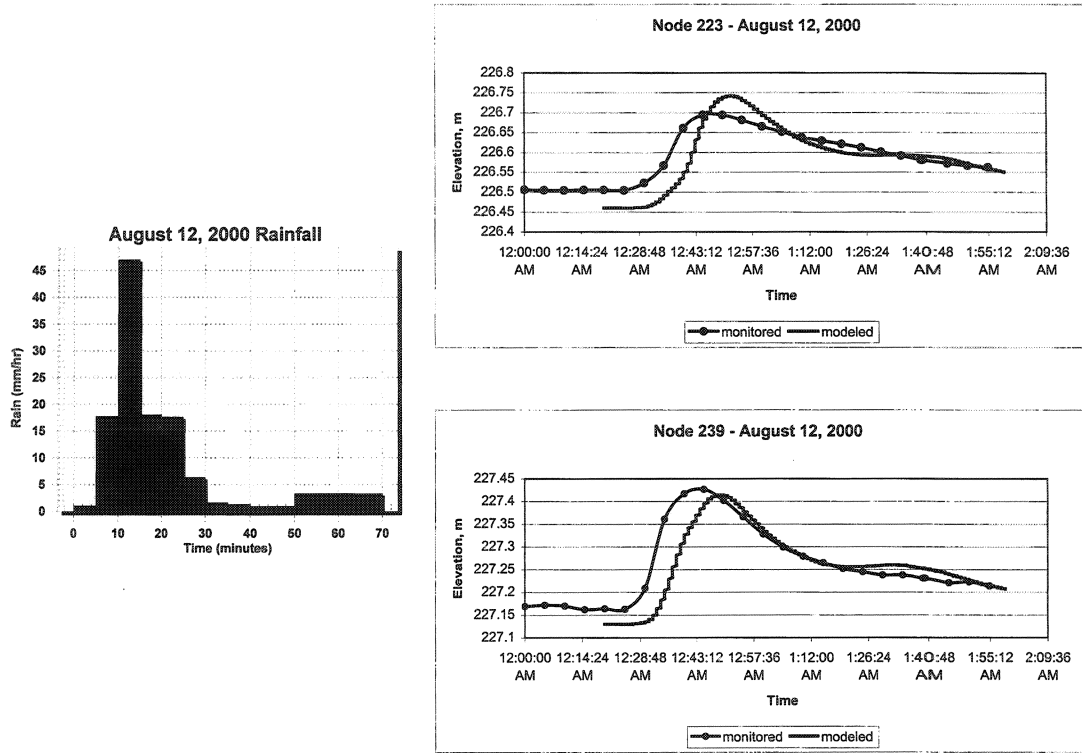


Figure 5.4 Rainfall hyetograph and computed stage hydrographs for the August 12, 2000 event.

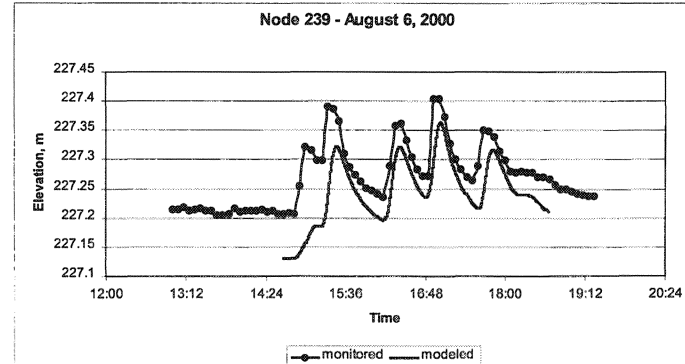
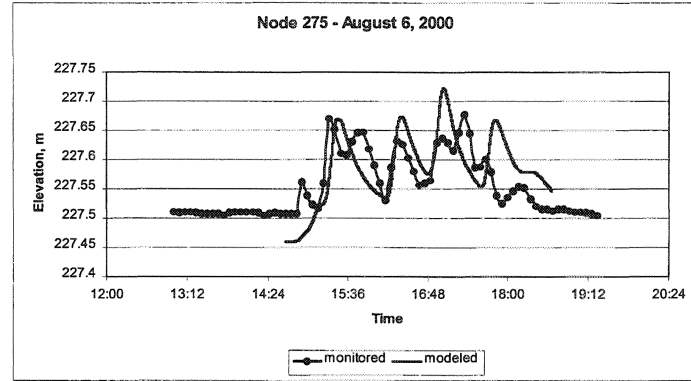
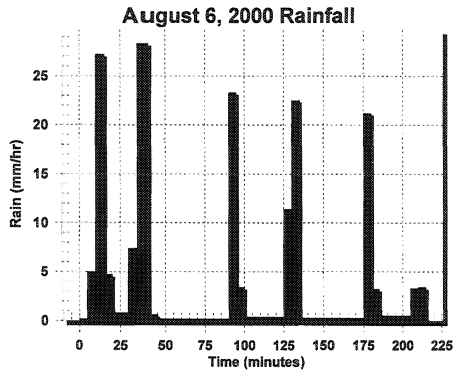


Figure 5.5 Rainfall hyetograph and computed stage hydrographs for the August 6, 2000 event.

- July 4 - 19.5 mm (0.77 in.) over 5.5 h
- July 7 - 58.3 mm (2.30 in.) over 5.5 h
- August 6 - 14.6 mm (0.57 in.) over 4 h

The verification exercise indicated that the model provided good correlation to observed data for all three events; however, only the August 6, 2000 event is discussed in detail in the following section as it provided a thorough test for the model

The August 6 event consisted of five separate, intense spikes of rainfall, as shown on Figure 5.5. In total, 14.6 mm (0.57 in.) of rain fell over a four hour period. Model comparisons to measured data at Node 275 (collector sewer) and Node 239 (trunk sewer) are also shown. These comparisons indicate a good match to the monitored peak levels as well as the overall shape. The model's ability to match the later spikes indicates that runoff from the pervious and impervious areas is modeled appropriately, since runoff would only occur from the impervious areas from the initial rainfall while the later rainfall would also result in runoff from pervious areas.

The calibration/verification analysis consisted of a review of the model results from five separate rainfall events. The calibration/verification analyses indicated that the model provides a very good representation of the combined sewer systems response to rainfall and could be used with confidence for the design of basement flood relief works. As a result, the model was deemed suitable for the economic analysis of the basement flood relief works.

5.4 Hydraulic Analysis

The detailed hydraulic analyses used the calibrated model to assess the existing level of basement flood protection in the District as well as assist with the conceptual design of relief alternatives to upgrade the combined sewer system to provide a five-year level of service.

5.4.1 Existing Level of Service

The extent of potential basement flooding was computed for the 1-, 2- and 5-y design storms (McLaren, 1974) by comparing basement and street elevations with the maximum hydraulic grade line predicted by the model. Figure 5.6 shows the basis for developing level of service criteria by applying the concepts of freeboard and model tolerance. For the purpose of establishing a basement flooding indicator, a 0.2 m (0.7 ft) freeboard was added to a 2.0 m (6.6 ft)

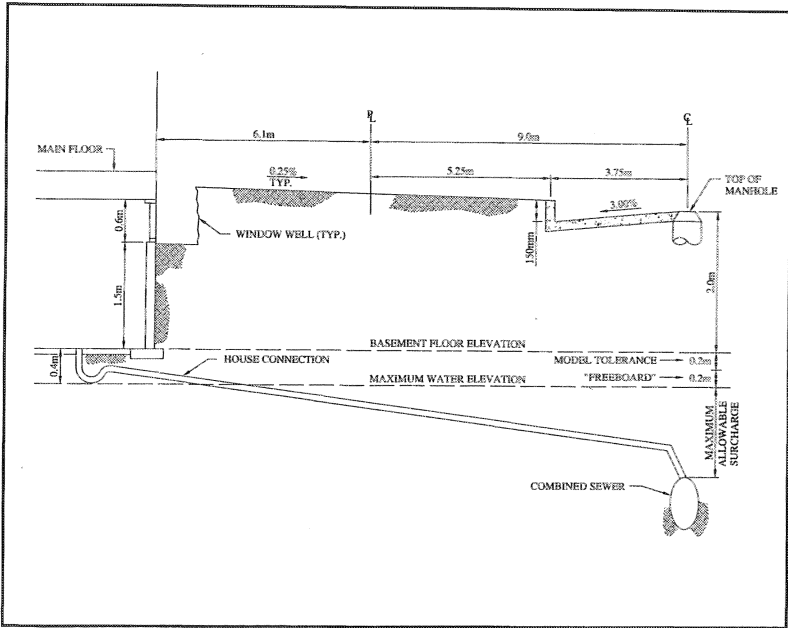


Figure 5.6 Comparison of basement and street elevations.

probable basement depth and 0.2 m (0.7 ft) computer model tolerance factor. Therefore, it was assumed that potential basement flooding would occur when levels in the system were within 2.4 m (7.9 ft) of the ground surface. This allowance provides a factor of safety in the ultimate operation of the system, since there are a variety of localized conditions for basement connections in an older system that can affect system performance.

The current level of service for the Dumoulin District combined sewer service area was determined by routing the City's design storms through the model and assessing the computed maximum water levels with respect to basement flooding. This information was also used to estimate the number of units with potential flooding damages, which is later used in the benefit-cost analysis of the relief alternatives. Total rainfall and peak intensities for the design storms used for the level of service analysis are shown in Table 5.1.

The existing level of service in the Dumoulin District is shown on Figure 5.7.

For the 1-y storm event, the computer model predicted basement flooding in 45% of the District and in the majority of the upstream lateral sewers. The Dumoulin combined sewer trunk, as well as the larger collector sewers flow

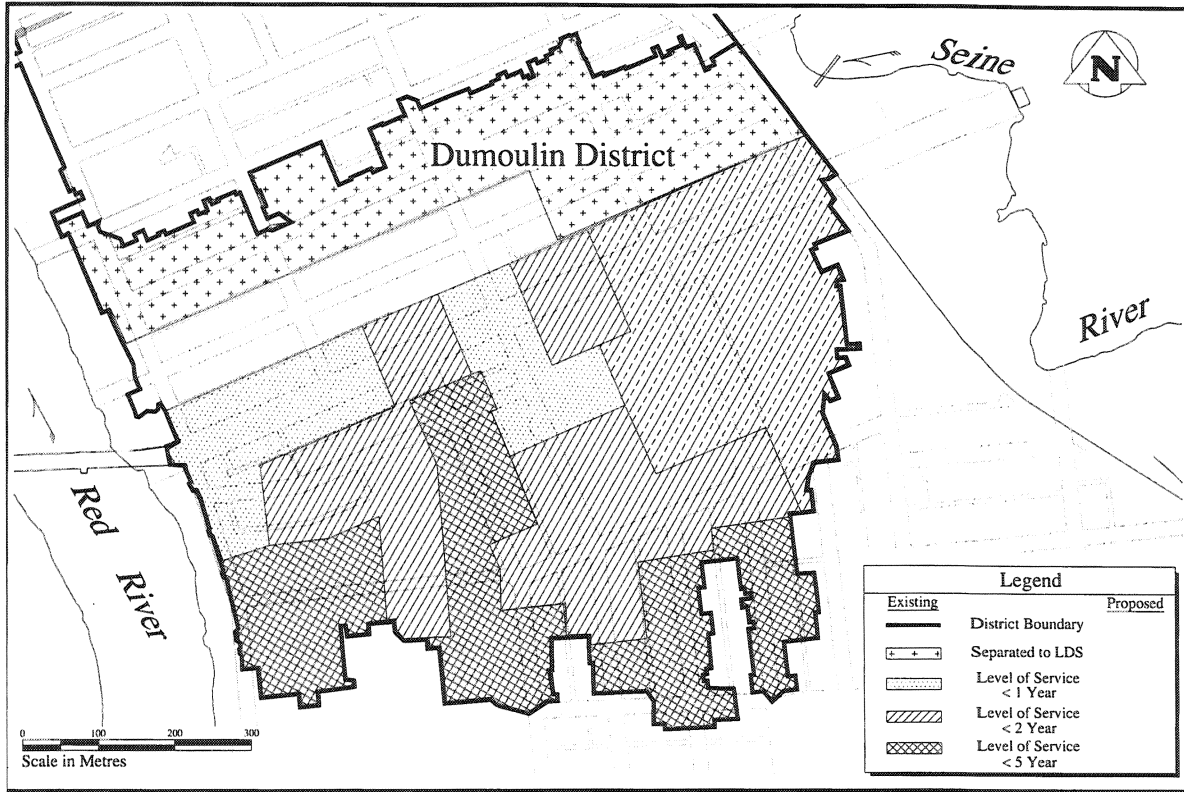


Figure 5.7 Existing level of service in the Dumoulin District.

Table 5.1 Winnipeg design storm data.

Rainfall Return Frequency	Total Rainfall (mm) for Storm Duration (h)	Peak Rainfall Intensity (mm/hour)	
		5 min.	15 min.
1-y	21 (1.8)	82	49
2-y	31 (2.5)	109	67
5-y	41 (3.0)	143	89

less than full for this event. This indicated that a lack of capacity in the upstream lateral sewers is a major factor in basement flooding in the District.

Basement flooding was computed in over 70% of the District, including the entire south and east portions of the district for the 2-y design storm event. Additional flooding (i.e. sewers surcharged to within 2.4 m (7.9 ft) of the ground) was computed for the remainder of the lateral sewers, collector sewers and the upstream portion of the trunk sewer. The trunk sewer, for the most part, flows below capacity.

The 5-y design storm analysis indicated potential basement flooding in over 85% of the district. The only locations without flooding were along the downstream portion of trunk sewers adjacent to the river. This indicated that the entire system is undersized and inadequate to convey flows from an event of this magnitude. The extent of the predicted basement flooding and the potential number of affected properties are summarised in the following table.

Table 5.2 Predicted basement flooding.

Return Event	Flooded Area	Number of Affected Properties			
		Residential	Multi-Family	Commercial	Public Use
1-y	45%	118	5	1	12
2-y	70%	193	6	11	18
5-y	85%	206	6	38	19

5.4.2 Relief Alternatives

The basic requirement of the City’s Basement Flood Relief Program is to provide a minimum 5-y level of protection. As identified in the existing level of service analysis, most of the existing combined sewer system does not have the capacity to handle the runoff generated from the 5-y design event.

The analysis of supplemental piping systems to upgrade the existing combined sewer level of protection included the following relief measures that were applied alone, or in combination, throughout the Dumoulin District:

- *Conventional Combined Sewer Relief* - Parallel Storm Relief Sewers (SRS) installed, as required, to augment the existing combined sewer system. The additional flow capacity in the relief piping reduces sewer surcharge below basement levels thereby eliminating potential basement flooding for the design event. DWF, and to a certain extent, wet weather flow (WWF) is contained in the existing piping system. Excess stormwater overflows from the combined sewer to the SRS.
- *Stormwater Separation* - New land drainage sewers (LDS) installed and collect runoff from the surrounding area. The removal, or separation, of the runoff is achieved when the remaining stormwater flows in the combined sewer are less than its conveyance capacity, and the subsequent depth of flow is below basement levels. The foregoing description meets the requirements of the basement flood relief program. In addition, total stormwater separation alternatives are investigated for potential integration with other City initiatives such as the combined sewer overflow management initiatives.

The hydraulic analysis for the conceptual design of relief measures was performed using the calibrated and verified model. Once the extent of the proposed piping was determined, construction cost estimates were prepared for each relief alternative. The costs were based on unit piping costs provided by the City along with best estimates for ancillary works such as riverbank stabilization, gate chambers, junction chambers, etc.

Prior to the development of the conceptual designs, a visual investigation of the riverbanks in the District was conducted. This helped identify the most desirable location(s) for new sewer outfalls, and conversely to identify those locations where extensive bank stabilization works would be required. This information was considered during the conceptual design and accounted for in the cost estimates to provide a realistic comparison between relief alternatives.

The current level of service analysis indicated that the 5-y design storm would result in potential basement flooding over approximately 85% of the combined sewer service area in the District. The nature of the flooding also indicated that the entire combined sewer system, trunk, collectors and laterals, lacked capacity for the design event. Accordingly, it was anticipated that any conventional combined sewer relief, as well as stormwater separation alternatives, would require a new outfall to the river. Therefore, the preferred outfall locations were considered in the development of the relief alternatives.

The cost of the proposed relief works warranted a thorough conceptual design to ensure that the most cost-effective plan was formulated. For the Dumoulin District eight different relief schemes were investigated. Two conventional combined sewer relief alternatives were conceptually designed with different outfall locations. A partial separation alternative determined that the separation of the south portion of the district would provide cost effective relief for the District. The most cost-effective 5-y relief scheme was found to be a combination of stormwater separation and conventional relief piping (alternative D5 in Table 5.3) and is shown on Figure 5.8.

In addition to the foregoing, two separate routing alternatives for future total stormwater separation were investigated. The recommended system was then analysed for upgrading considerations for compatibility with potential future separation. The relief alternatives, level of service and construction cost estimates are summarized in Table 5.3.

Table 5.3 Relief alternative comparison.

Alternative	Relief Option	Level of Service	Construction Cost
D1	Combined Sewer Relief	5-y	\$1,765,000
D2	Combined Sewer Relief	5-y	\$2,330,000
D3	Partial Separation	5-y	\$1,795,000
D4	Total Separation – Cathedrale Outfall	5-y+	\$2,510,000
D5	Combination of Partial Separation and Combined Sewer Relief – Recommended	5-y	\$1,500,000
D6	Alternative D5 Oversized for Future Total Separation (D4)	5-y	\$1,708,000
D7	Total Separation – Outfalls on Cathedrale and Masson	5-y+	\$2,521,000
D8	Alternative D5 Oversized for Future Total Separation (D7)	5-y	\$1,530,000

5.5 Economic Analysis

The benefit-cost analysis of proposed relief alternatives provides an analytical approach for comparing the cost of public works projects to the tangible, or quantifiable, benefits of providing the service. Project costs include construction, engineering, finance, and administration as well as the loss on investment (return on investment generated by capital if invested at an interest rate in excess of inflation). The tangible benefit of providing basement flood relief works is the reduction in flooding damages.

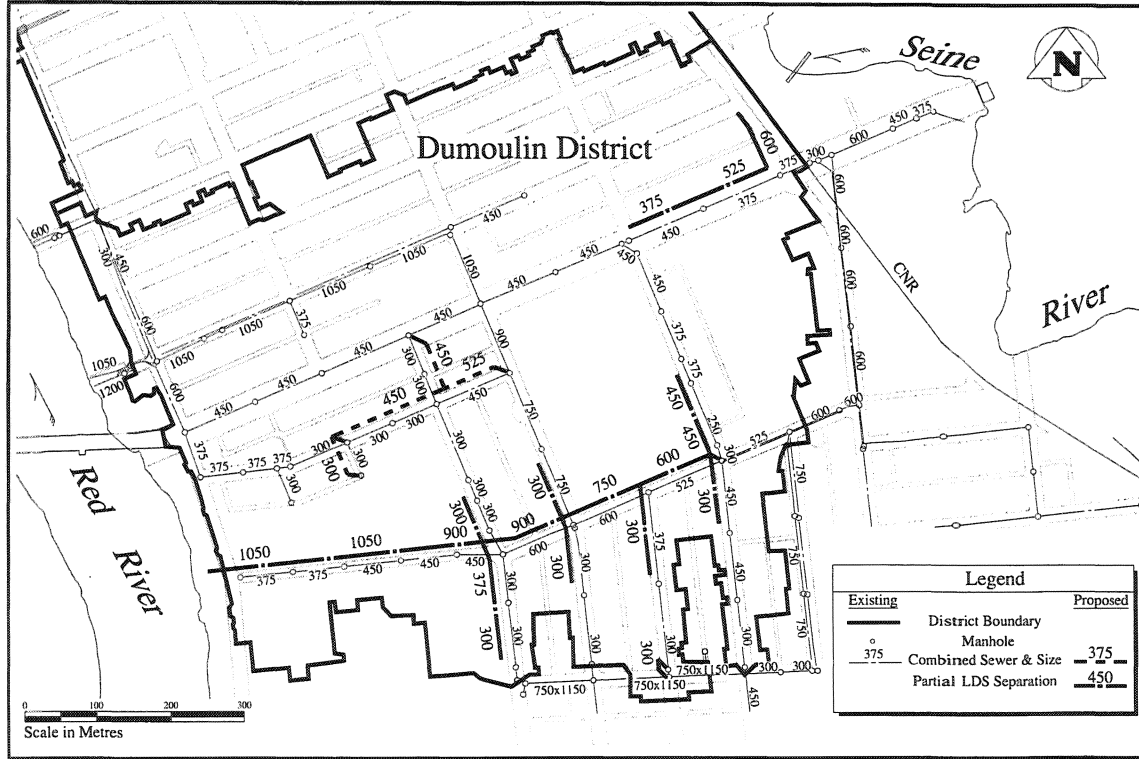


Figure 5.8 The most cost-effective 5-y relief scheme.

The economic analysis is typically carried out with an annual worth comparison (City of Winnipeg Waterworks, Waste and Disposal Department, 1986). The annual worth comparison requires a common time frame for the comparison of costs and benefits. This is an arbitrary assignment as the benefits of the piping system are expected to accrue over a longer period than the project financing; however, to provide a common basis for the program, a design period/amortisation period of 50 y is used.

5.5.1 Annual Costs

Construction costs were estimated for each of the relief alternatives investigated for the Dumoulin District. Total project costs were estimated by including burdens and the opportunity costs of investing in public works projects. Project burdens are associated costs carried by the City, and include engineering costs, as well as City administration and financing charges. The total burdens are estimated at 20% of the construction cost based on the following proportions:

- 12% for engineering
- 7% for City finance (incl. 3% for applicable sales/service taxes)
- 1.0% for City administration

Total project costs also consider the investment costs of financing public projects, i.e. the potential loss on investment if the funds were invested at an interest rate in excess of inflation. This rate is commonly referred to as the social discount rate. It cannot be clearly identified over the amortisation period but it is assumed that 4% provided for a normal range of economic conditions.

The following formula is used to calculate annual project costs:

$$A = \frac{P * i * (1 + i)^n}{(1 + i)^n - 1}$$

where:

- A = annual cost,
- P = project cost, including burdens,
- i = social discount rate, and
- n = amortisation period.

5.5.2 Benefits

The benefits of upgrading basement flood relief were calculated as the difference between annual damages in the District before and after implementation of the relief measures. Potential flooding was estimated with the

computer model based on the extent of the flooding from the 1-, 2- and 5-y events. In addition, damages were also calculated for the entire district from a catastrophic flooding event, referred to as Complete District Flooding (CDF).

The basic assumption in calculating the incidence of basement flooding is that not all homes in a flooded area have basement flooding, and if flooded, not all homes suffer damages. The number of flooded basements varies with storm size and can be represented mathematically using the following formulae in which F is the percent of the district with predicted basement flooding (City of Winnipeg, 1986):

Return Period	Damage Ratio
1-y	0.1
2-y	$0.1 + F/1000$
5-y	$0.1 + F/450$
Complete District Flooding (CDF)	0.55

Flooding damages were assigned the following values, derived from average damage claims reported in the City:

- \$1,250 for residential units,
- \$8,750 for commercial buildings,
- \$6,250 for multiple dwellings,
- \$12,500 for industrial facilities,
- \$12,500 for public facilities,
- \$12,500 for schools, and
- \$18,750 for hospitals.

This information was used to calculate the total damages for each event as shown in Table 5.4. The data was then plotted as shown in Figure 5.9. The area under the curve represents the average annual damages before relief works are installed. For the Dumoulin District the average annual damages are \$169,249.

The next step in the analysis was to calculate the residual damages, or the flooding damages that might still occur after relief works were implemented. This was carried out for each alternative. Since the design criterion is a 5-y level of protection, larger events (e.g. a 10-y storm) could cause flooding. The residual damages were estimated based on the type of relief system. Residual damages for conventional combined sewer relief works were estimated based on the complete district flooding value and are also shown on Figure 5.9. The annual benefit of the relief works was then calculated based on the area between

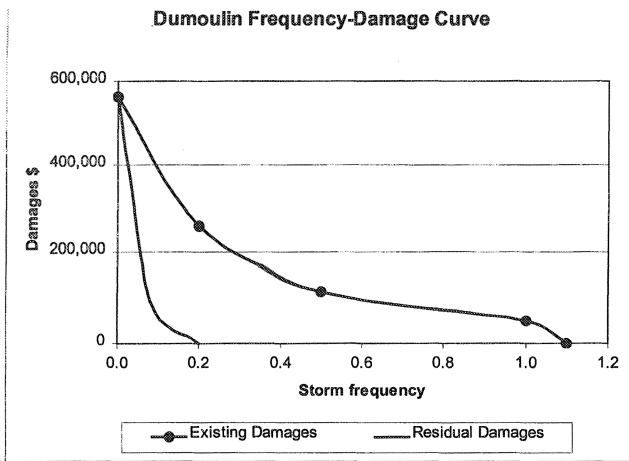


Figure 5.9 Dumoulin frequency-damage curve.

the two curves. Residual damages for total stormwater separation are assumed to be zero since stormwater does not enter the combined sewer system. For partial separation alternatives, damages were reduced according to the percentage of the District that was separated.

Table 5.5 provides the results of the benefit-cost analysis of the Dumoulin District hydraulic relief alternatives.

The foregoing analysis indicates that all of the relief alternatives have a positive benefit-cost ratio, i.e. greater than 1.0. The recommended relief alternative (D5) provides 5-y relief at the least cost and at the highest benefit-cost ratio (1.86). The results of the economic analysis provide the financial justification to proceed to the construction phase, although the timing may be dependent on comparisons with other district studies and their associated benefit-cost ratios.

5.6 Conclusions

Implementation of the Basement Flood Relief Program requires the expenditure of considerable public funds. Economic analysis of the program ensures that relief projects are administered in a financially responsible manner. The benefit-cost analysis provides a methodology to compare the tangible benefits of the project, as well as provide a means of ranking individual districts for priority relief implementation.

Table 5.5 Dumoulin District – benefit-cost analysis of hydraulic relief alternatives.

Relief Alternative	Description	Construction Cost	Total Cost (c/w burdens)	Annual Worth	Existing Damages	Residual Damages	Annual Benefits	BC Ratio
D1	Combined Sewer Relief	\$1,765,000	\$2,118,000	\$98,593	\$169,249	\$30,375	\$138,874	1.41
D2	Combined Sewer Relief	2,330,000	2,796,000	130,154	169,249	30,375	138,874	1.07
D3	Partial Separation	1,795,000	2,154,000	100,269	169,249	9,113	160,136	1.60
D4	Total Separation	2,510,000	3,012,000	140,209	169,249	0	169,249	1.21
D5	Combination of Partial Separation and CS Relief - Recommended	1,499,850	1,799,820	83,782	169,249	13,669	155,580	1.86
D6	Alternative 5 Oversized for Future Total Separation (D4)	1,708,000	2,049,600	95,409	169,249	30,375	138,874	1.46
D7	Total Separation – Two Outfalls	2,521,000	3,025,200	140,824	169,249	0	169,249	1.20
D8	Alternative 5 Oversized for Future Total Separation (D7)	1,530,075	1,836,090	85,470	169,249	13,669	155,580	1.82

SWMM modeling provides the necessary hydraulic analysis data to carry out the economic analysis. Using a calibrated model to assess the existing level of flood protection for various return frequency events allows the calculation of flooding damages on an annual basis. The same model is also used to define relief requirements to the extent that detailed cost estimates can be estimated. The annual worth comparison provides a reliable financial framework for comparing benefits and costs of basement flooding relief projects.

References

- City of Winnipeg, 1986, Waterworks, Waste & Disposal Department, Basement Flooding Relief Program Review - 1986, November 1986.
- McLaren, James F. Limited, 1974, Drainage Criteria Manual for the City of Winnipeg, November 1974.
- Steiss, G. and W.D. Watters. 2001. "Developing a Model for Basement Flood Relief Works for the New Millennium." *Journal of Water Management Modeling* R207-15. doi: 10.14796/JWMM.R207-15.
- Wardrop Engineering Inc. and TetrES Consultants Inc., 1995, Combined Sewer Overflow Management Study, Phase 2 Priority Field Inspection Report, District Diversion Structures and NEWPCC Interceptor Sewers, May 1995.
- W.L. Wardrop & Associates Ltd., 1963, Sewer Replacement Program, Area Between Seine and Red Rivers, City of St. Boniface, April 1963.

