

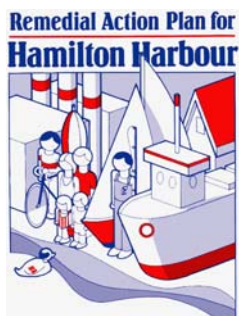


Hamilton Harbour RAP Water Quality Goals and Targets Review

**Part 1: Response to the City of Hamilton's
Proposed Wastewater System Upgrades**

TECHNICAL APPENDIX

July 2007



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1. Introduction

Hamilton Harbour is a large embayment located at the western tip of Lake Ontario. It has a long history of water pollution, and as such was deemed an Area of Concern (AOC) under the Great Lakes Water Quality Agreement (1987). Of particular concern in the Harbour are the issues associated with eutrophication, or the excessive nutrient loading to the Harbour that results in algal blooms, undesirable algae, and bottom waters devoid of oxygen during the late summer. While water clarity has improved in the Harbour since 1990 and aquatic macrophytes have seen a significant resurgence in most areas of <3 m in depth, algal blooms have continued to be a nuisance and hypolimnetic oxygen concentrations remain low.

Developing appropriate nutrient load reductions in order to address the multiple eutrophication impacts is a complex task; an example of this complexity are the targets for ammonia and phosphorus as “[t]he proposals for addressing ammonia and phosphorus relate to the low oxygen conditions in the bottom waters of the Harbour in summer, and to the clarity of water” (HH RAP, 1987, p.7), which are separate issues being driven by one solution (target). While a reduction of nutrients to the Harbour is an obvious step towards the solution of these identified problems, there are many interactions and processes in the Harbour that make developing these solutions more complex than originally perceived.

For example, a reduction in total phosphorus (TP) to the Harbour is expected to result in a reduction of algae blooms, because TP stimulates algae growth. Algae blooms play a role in raising the pH of the Harbour due to removal of CO₂ during photosynthesis. The rising of the pH plays a role in ammonia toxicity as a larger percentage of ammonia is un-ionized (toxic form of ammonia) with higher pH values. Therefore, a reduction in TP to the Harbour, leading to less algae blooms and associated alterations to the pH, is also expected to play a role in reducing potential un-ionized ammonia toxicity issues, which are generally approached quite separately.

An ecosystem approach was used in setting the water quality concentration and loading targets for Hamilton Harbour. This included the consideration of many of these complex interactions in developing goals for abiotic parameters that control the biotic components of the Harbour. For example, fish need aquatic plants for shelter and reproduction, aquatic plants need light to grow, light will only penetrate the water column if chlorophyll *a* (algae) levels are sufficiently low, low chlorophyll *a* levels are achieved through sufficiently low TP concentrations, and low Harbour TP concentrations are a function of the total TP load to the Harbour. Following this approach used by the RAP and using TP as an example, TP loading goals were set based on how these loads would support a warm water fishery in the Harbour, deemed a priority use for the Harbour by stakeholders during an initial RAP meeting in 1987 (p.3.24 of MMM, 1988).

However, the task of choosing a single number (or range) as a final goal for a particular parameter is extremely challenging. Much debate was put into the selection of one number that represents a balance between many conflicting priorities; adding to this challenge is the scientific uncertainty regarding the conditions expected with the selected parameter value. The difficulty in selecting target values is reflected in the historical RAP literature review through the mention of several values all intended to address similar goals for environmental conditions in the

Harbour. The Technical Team during the early stages of the RAP development (late 1980s) had to ‘juggle’ the variously modelled predictions of Harbour conditions, the ‘value’ of different parts of the Harbour, the cost and/or feasibility of various remedial measures in differently designed WWTPs, equity between Regions and the varying perceptions of the members of the Stakeholders and Forum groups that had to be addressed (K. Rodgers, personal communication, 2007).

Despite the challenges inherent in the RAP process, concentration and loading targets for the Hamilton Harbour AOC were set. Loading targets have been used by industry and municipalities to guide decision making on upgrades necessary to remediate Harbour waters. Currently, the City of Hamilton is developing their Water and Wastewater Master Plan that “presents a strategy for water and wastewater infrastructure to service existing and new growth in the City for the 2031 planning period” (p.1, KMK, 2007). This Master Plan will see major upgrades to the Woodward Avenue WWTP and with these upgrades, changes to effluent concentrations and loadings (Table 1). The City of Hamilton in establishing design objectives for its soon-to-be upgraded wastewater treatment system purposefully used the HH RAP final effluent targets for the Woodward WWTP and CSOs, as no additional upgrades to the system will be occurring before the RAP proposed delisting date of 2015. In Phase 1 + 2 of the Master Planning for the wastewater treatment system, the City identified how close it can come to meeting these HH RAP effluent targets using best available technology and considering cost effectiveness.

Table 1: Woodward Avenue WWTP and CSO RAP Target Loadings relative to Current Loadings and Effluent Design Objectives

	Current Loading (kg/d)	Proposed Loading (kg/d)		RAP Final Loading (kg/d)		Difference Between Proposed and Final Reductions
		(% reduction from current)				
Woodward WWTP						
Ammonia	2971	1000	(66%)	530	(82%)	16 %
Total Phosphorus	207	74	(64%)	60	(71%)	7 %
Total Suspended Solids	6918	1488	(78 %)	900	(87%)	9 %
CSO System						
Ammonia	117	48	(59%)	20	(83%)	24 %
Total Phosphorus	46	8	(83%)	5	(89%)	6 %
Total Suspended Solids	2396	329	(86%)	200	(92%)	6 %

*Note: For CSOs, proposed loadings are based on modelling simulations using 1988 and 1989 rainfall data

This Technical Appendix to the *Hamilton Harbour RAP Water Quality Goals and Targets Review – Part 1: Response to the City of Hamilton’s Proposed Wastewater System Upgrades* report aims to fulfil two primary objectives:

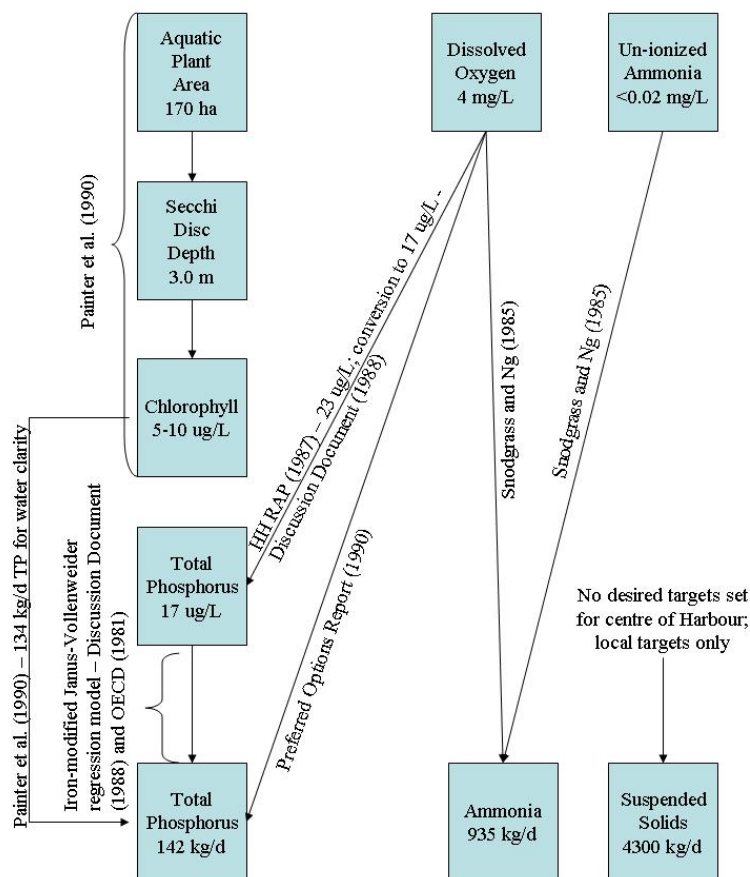
- 1) It provides an examination of the historical development of eutrophication-related loading and concentration RAP goals that have been set for Hamilton Harbour. This historical reconstruction was used to contribute towards a preliminary review of the ability of RAP

goals to achieve desired environmental conditions in the Harbour (Figure 1), that will be built upon during Part 2 of this report series; and

- 2) It runs parallel to the summary report by providing additional detail on the findings summarized in Section 5. Thus, it also examines if the City of Hamilton’s proposed effluent targets support the Hamilton Harbour RAP’s concentration goals and associated desired conditions for the Harbour.

These two objectives were undertaken in tandem to ensure that the proposed effluent conditions from Woodward Avenue WWTP were evaluated against the most current perspective of how Hamilton Harbour has responded to clean-up efforts, and what conditions are necessary to bring the Hamilton Harbour AOC towards delisting in 2015. This evaluation by the HH RAP Technical Team is being carried out in parallel with the City of Hamilton’s Master Planning to assist in the implementation of this preliminary RAP review.

Figure 1: Relationships and references used to develop final RAP loading targets based on desired environmental conditions for a warm water fishery



2. Suspended Solids

2.1 Suspended Solids Primer

Elevated levels of suspended solids in the water column leads to reduced water clarity; this is of concern due to aesthetic impact, as well as the links to ecosystem functioning. An over abundance of suspended solid particles in the Harbour blocks sunlight from reaching submerged plants (macrophytes), thus reducing potential fish habitat. There is no provincial water quality objective (PWQO) for suspended solids, except indirectly in how it may relate to turbidity. The PWQO for turbidity states that *suspended matter should not be added to surface water in concentrations that will change the natural Secchi disc reading by more than 10 percent.*

2.2 Suspended Solids in Hamilton Harbour

Because degraded aesthetics and a loss of macrophytes were concerns for Hamilton Harbour during the development of the Hamilton Harbour RAP, a reduction in the loadings of suspended solids to the Harbour and corresponding concentrations in the Harbour were goals set to address these impaired beneficial uses. This was especially true of Cootes Paradise, where suspended sediments were particularly problematic after large rainfalls and due to carp activity. While algae was the major cause of reduced water clarity in the Harbour (algae responsible for 10-30% of total water clarity impairment in Hamilton Harbour, p.3, Discussion Document, 1988), suspended solids was determined to be the major cause in Cootes Paradise (algae only responsible for 10% of water clarity impairment in Cootes Paradise, p.3, Discussion Document, 1988). The strong connection between algal concentrations in Hamilton Harbour and water clarity was observed especially in 1997; a cool spring and an intense zooplankton bloom resulted in Secchi depth measurements of greater than 5 m (Charlton, 2001).

2.3 Historical Recounting of Suspended Solids Goal and Target Decisions

Details and interpretation on the historical development of RAP concentration and loading goals pertaining to suspended solids are described in Sections 2.3.1 to 2.3.5.

2.3.1 Painter et al. (1988)

A report by Painter et al. (1988) indicated that loadings of seston (suspended solids) from the Cootes Paradise watershed would have to be reduced by 50% to restore aquatic vegetation in Cootes Paradise. This is because reduced water clarity in Cootes Paradise was attributed primarily to elevated seston concentrations relative to algal biomass; therefore, remediation efforts to restore Cootes Paradise were focused on seston. Some degree of modelling was undertaken and it was stated that seston concentrations would have to decrease to concentrations below 15 mg/L to achieve sufficient water clarity for submergent plant growth (p.21). It is not clear how the seston work outlined in Painter et al. (1988) is transferable to seston concentrations

and issues in Hamilton Harbour. It is however interesting to note that to achieve the desired water clarity (>75 cm Secchi depth) to promote submergent plant growth in Cootes Paradise, the incoming seston in Spencer Creek would have to be reduced from 20 to probably 10 mg/L (p.29).

2.3.2 Stage 1 Report (1992)

To address the water clarity issues in the Harbour, the HH RAP Stage 1 Report (1992) stated that suspended solids loadings should be reduced by 50% (p.170). Figure 43 in this report (p.179) reiterated the connectivity between seston and water clarity, with expected water clarity results of 180 cm and/or 240 cm, leading to an area of 100 ha and/or 115 ha of submerged plants, respectively. This figure also gives a suspended solids proposed target of 45,000 kg/d from streams, based on total 1987 loadings of 50,000 kg/d. There is no reference as to how the target of 50% was derived; however, it is likely connected to the 50% reduction in seston loadings to Cootes Paradise deemed necessary to address desired water clarity in Cootes Paradise to promote submergent plant growth (Painter et al., 1988). While water clarity was the primary criterion used to develop the suspended solids target, it was also mentioned (p.159) that a reduction of suspended solids loads would have a secondary impact of reducing particle-bound contaminant loads to the Harbour (e.g. metals, organic contaminants).

2.3.3 Stage 2 Report – Summary (1992)

The Stage 2 Report (1992) outlines suspended solids loadings to the Harbour from 1978 – 1989 and also specifies the contribution by source for 1989 loadings (p.73). The discussion surrounding the contribution of suspended solids loadings by each source indicates that “[o]ne should probably not point to a single dominant source from this perspective since the impact tends to be most evident close to the entry point of each individual source. While reduction of any one of these sources could benefit the Harbour as a whole, the improvement in the nearshore areas close to where it [enters] into the Harbour will be the most noticeable” (p.72). Thus, the concern over suspended solids loadings to the Harbour was focused on local aesthetic impacts related to water clarity. The focus on local area impacts is again emphasized by the statement that “while creeks, urban runoff, and Cootes Paradise loadings are sometimes smaller units, their area of impact is critical and thus they probably should receive higher priority” (p.74). Such priority is again mentioned in the evaluation of potential remedial actions for suspended solids control, as it is stated that “siltation of estuaries and marsh areas is a major consequence of loadings from the creeks and streams. In these locations they damage the habitat and then are available for resuspension by wind or carp activity. Strategically, the discharge of suspended solids into these shallow areas may be more critical than other discharges” (p.75). While this last statement is also focused on local impacts and is consistent with other statements, it alludes to a connection between suspended solids targets and desired ecosystem goals (i.e. habitat).

The Stage 2 Report (1992) re-iterates a point mentioned in the Stage 1 Report (1992), that being the ancillary issue of the contaminants that solids may carry, with the example provided that reductions in total phosphorus loadings are effectively achieved by reducing suspended solids discharge (p.72). This is again noted on page 74 and stated that “[m]easures to reduce

toxic chemical loadings, ammonia loadings and phosphorus loadings are achieved by removing suspended solids from the wastewater flow. Hence, attention to these factors provides a large measure of relief from 50 percent of the suspended solids loading estimated for 1989. Indications are that implementing phosphorus control ... will remove 50 to 70 percent of the [suspended solids] loading from the STPs”.

Current actions and potential remedial actions for suspended solids control are listed on pages 74-77 of the Stage 2 Report (1992); 6 of the 10 actions listed have to do with watershed-based initiatives. In the evaluation of these potential remedial actions, further information is indirectly provided on the purpose of the targets for suspended solids in Hamilton Harbour. The potential remedial actions are consistent with addressing aesthetic impacts, promoting swimmable areas, reducing frequency of dredging/the need for confined disposal facilities (CDFs), and ensuring adequate fish habitat. The relation of suspended solids with these problems is also specified in Figure 3 of the Stage 2 Report (1992, p.34) where suspended solids are demonstrated to be linked to: 1) poor water clarity; 2) silting in, and toxics in sediment, CDF's; and 3) infilling, Marsh Loss.

The Stage 2 Report (1992) provides objectives to be achieved in order to permit delisting of the Hamilton Harbour AOC. These objectives are listed in Table A of the report, and are listed by use impairment. Under use impairment “Eutrophication or undesirable algae”, net loading targets for suspended solids are listed as outlined in Table 2 below. The original table in the Stage 2 Report (1992) notes that for streams, loadings are extremely variable from year-to-year and the percentage of reduction is based on the estimated effect of best management practice.

Table 2: Net Loading Targets for suspended solids (kg/d) as listed in HH RAP Stage 2 Report (1992, p.225)

	Initial Goal	Final Goal
Hamilton STP	3750	900
Burlington STP	500	200
CSOs	1400	200
Streams	30,000	20,000
Stelco	4000	1500
Dofasco	3500	1500
Total	43,150	24,300

The corresponding table in the report for target environmental conditions does not list an initial or final goal for suspended solids concentration in Hamilton Harbour, but does list final goals only for Cootes Paradise (10 mg/L) and Grindstone Creek Area (10 mg/L). These targets of 10 mg/L for Cootes Paradise and Grindstone Creek Area are consistent with the suspended solids concentrations deemed necessary for these areas outlined in Painter et al. (1988).

Although net loading targets are set for a number of sources to the eastern part of Hamilton Harbour (STPs, CSOs, industry), the desired water quality improvements from meeting the final goals are for Cootes Paradise and the Grindstone Creek area. Suspended solids conditions were not set for the main body of Hamilton Harbour despite strict loading targets for

sources of suspended solids to Hamilton Harbour, because water clarity in the Harbour had a stronger link to algal productivity over suspended solids, relative to conditions in Cootes Paradise (p.3, Discussion Document, 1988). In addition to this, impacts from suspended solids loads to the Harbour were generally discussed in terms of meeting very localized water clarity goals due to different ‘values’ or ‘uses’ of these parts of the Harbour (K. Rodgers, personal communication, 2007), providing little reason to develop a Harbour-wide suspended solids concentration goal. It was assumed that the areas of interest would see improvements to water clarity when suspended solids loads directly impacting those areas were reduced to the RAP loading goals set.

Also in the Stage 2 Report (1992), actions required to address recommendations are listed in Table 8 of the report by responsible agencies and task. One of the tasks specified for the OMOE and EC is to develop models based on recent data to predict the impact of new ammonia, phosphorus, and suspended solids loadings reductions, in order to gauge the cost-effectiveness of each remedial measure as it is implemented (p.153). While much work has gone into examining the relationship between phosphorus and ammonia loadings and Harbour conditions (McMahon and Snodgrass, 1993), there has been no equivalent effort to gauge the impact of suspended solids loading reductions on Harbour water quality. This is understandable given the absence of explicit suspended solids related ambient water quality targets for the Harbour.

2.3.4 1998 Status Report (1998)

In the HH RAP 1998 Status Report (1998), Figure B3 shows Harbour suspended solids loadings and concentrations for the period 1978 – 1996. The initial and final RAP loading targets are shown on the histogram and are visually consistent with loading targets of 43,150 and 24,300 kg/day, respectively, as presented in Table 2 above. Visual inspection of Figure B3 in the 1998 Status Report (1998) also reveals that the prescribed 50% reduction of suspended solids loadings was based on calculated Harbour loadings for 1988, as 24,300 kg/day (final loading target for the Harbour) is half of the 1988 suspended solids loadings to Hamilton Harbour. While raw data are not available to confirm exact loading numbers for 1988, the 1988 loadings are less than 1987 and greater than 1989, and 1987 loadings have been accepted as 50,000 kg/day (based on HH RAP Stage 1 Report, p.179) and 1989 loadings as 44,981 kg/day (p.162, Stage 1 Report, 1992; p.73, Stage 2 Report, 1992). It therefore seems reasonable that 1988 loadings were 48,600 kg/year – two times the final suspended solids loading target.

2.3.5 Stage 2 Update 2002 Report (2003)

The suspended solids loading and concentration targets for Hamilton Harbour persisted throughout Stage 2, but underwent some modifications by the Water Quality Task Group (2000) to arrive at the current loading and concentration targets. The net loading targets for Hamilton Harbour as listed in the Stage 2 Update 2002 (2003) are presented in Table 3 below.

Table 3: Net Loading Targets for suspended solids (kg/d) as listed in Stage 2 Update 2002 (2003), p.26

	Initial Goal	Final Goal
Hamilton STP (Woodward WWTP)	3750	900
Burlington STP (Skyway WWTP)	500	200
Dundas WWTP	28	-
Waterdown WWTP	5	-
CSOs	1400	200
Streams	-	-
Stelco	4000	1500
Dofasco	3500	1500
Total	13,183	4300

This table differs from that presented in 1992 due to inclusion of the Dundas and Waterdown WWTPs, and the elimination of targets related to streams. There is only an initial goal for both the Dundas and Waterdown WWTPs, because both plants were already benefiting from tertiary treatment and falling short of the initial goal. The final goal is equal to the initial since this was the most realistic improvements possible following optimization of their tertiary systems (the failure of the total Harbour final goal to include this additional 33 kg/d in the total of 4300 kg/d is not significant given that this is less than 1% of the total load). The development of (initial) goals for the Dundas and Waterdown WWTPs follows the recognized environmental importance of TSS to Cootes Paradise and the Grindstone Creek delta area. The lack of clarity regarding a final goal for the Dundas and Waterdown WWTPs is not a major issue considering the current average TSS loads and future planned management strategies for both plants. The 2006 annual average TSS loads for Dundas and Waterdown WWTPs were 18 kg/d and 5 kg/d, respectively, meaning the Waterdown WWTP TSS load is coinciding with the initial TSS RAP goal of 5 kg/d, and the Dundas plant is well below the initial TSS RAP goal of 28 kg/d. TSS goals for these plants should also be considered in light of future management strategies as both plants rely on the Woodward Avenue WWTP, which is discussed separately in terms of this plant meeting its RAP TSS targets. The Dundas WWTP will be run as close to a steady flow as possible to stabilize the process, with excess flow to be sent to Woodward Avenue WWTP. The Waterdown plant will be decommissioned and all of these flows will be diverted to Woodward Avenue WWTP (M. Bainbridge, personal communication, 2007).

The elimination of stream loading targets follows the comment originally stated in the Stage 2 Report (1992) and repeated in the Stage 2 Update 2002 (2003) report that stream loadings are extremely variable and “are not directly comparable to suspended solids loadings from point sources because they are fundamentally different materials” (p.5, WQTG, 2000). This decision to eliminate stream RAP loading targets may also have considered results of a study undertaken by the MOE in 1988 that found control of non-point sources may only be able to reduce suspended solids (and phosphorus) loadings by 30-40%, instead of the former prediction of 50% (HH RAP, 1989, “Dialogue on HH”). It should be reiterated here that the original final loading target for the Harbour (24,300 kg/day) was assumed derived from total

1988 loadings that included stream loadings, and loading targets for other sources were parceled out based on these total 1988 loadings.

It should be noted that as recommended in the Stage 2 Update 2002 (2003), a separate RAP Technical Working Group, led by the RBG, is developing water quality requirements for the Cootes Paradise Marsh, including phosphorus and sediment loadings.

2.4 RAP Technical Team Opinion

Because the final suspended solids loading target for the Harbour was based on an agreed upon yet somewhat subjective 50% load reduction, and the load reduction was based upon estimated 1988 loadings¹, any parceling out of the final target to the individual sources also carries with it the uncertainty inherent in use of the target (50%) and the expected outcome, and the comparability of suspended solid loads in 1988 relative to more-long term trends. Combined with the lack of any ambient Harbour initial or final goal for suspended solids concentrations, this makes it difficult to justify the suspended solids final loading targets for the WWTPs, CSOs and industry. This is particularly important at the Woodward Avenue WWTP since the final suspended solids loading target (900 kg/d) would translate into a final effluent concentration requirement of approximately 1.8 mg/L at 500 ML/d flow (KMK Consultants Limited, 2007). In its master plan, the Woodward Avenue WWTP is proposing a final effluent total suspended solids concentration of 3 mg/L (KMK Consultants Limited, 2007).

Going beyond current proposed effluent objectives (3 mg/L) to meet RAP final loading targets (~1.8 mg/L) would significantly increase WWTP capital and operating costs for benefits which are not clearly linked to receiving water quality conditions in the (centre of the) Harbour. Although it is likely that through meeting the HH RAP loading targets for phosphorus, WWTP effluent will also see a net reduction in suspended solids loading, any reduction in phosphorus loading is and should remain a nutrient loading issue linked to the nutrient status of the Harbour.

Therefore it is recommended that the RAP suspended solids final loading targets for the Harbour from WWTPs and CSOs be addressed indirectly through measures specifically developed for phosphorus removal and best available technology as presently proposed by the City of Hamilton. The substantial suspended solids reduction proposed by the City of Hamilton from 6918 kg/d to 1488 kg/d is supported by the HH RAP Technical Team. This review highlights the need to re-examine a focus on watershed sediments in order to provide the most cost effective reductions in sediment loading (i.e. through stormwater management and stewardship).

3. Phosphorus

¹ HH RAP's choice in the late 1980s of the year 1988 as a base year to generate suspended solids loading targets is completely separate from the reasons for the choice of 1988 as a base year for the modelling efforts being undertaken by KMK on behalf of the City of Hamilton in their master plan wastewater simulations. It is merely coincidence that both processes used 1988 as a model or base year.

3.1 Phosphorus Primer

Phosphorus is a component of organic matter and an essential nutrient to cell growth. It is found in many forms, such as particulate and dissolved fractions (e.g. soluble reactive phosphorus (SRP)), but all these forms together are commonly referred to as total phosphorus (TP). Because of the ratio of nitrogen to phosphorus required to stimulate growth and the wide availability of nitrogen in aquatic systems, many water bodies are phosphorus-limited. This means that phosphorus concentrations play a large role in determining the productivity of a water body and additional inputs can be a cause of increases in productivity; this can be observed through algal blooms and overall this process is referred to as eutrophication.

There are many natural sources of phosphorus in the environment but when there is concern over excess phosphorus concentrations in a water body, i.e. eutrophication, it is usually due to excess anthropogenic inputs. Major anthropogenic sources of phosphorus to water bodies include waste water treatment plant (WWTP) effluent, and stream water due to entrainment of agricultural and urban runoff.

The impacts of excess phosphorus inputs resulting in eutrophication are usually deemed undesirable for many reasons. To begin with, algal blooms impact aesthetics due to odour issues and the reduction of water clarity. Also, the deposition of algal mass to the lake bottom following an algal bloom results in an increased hypolimnetic dissolved oxygen demand as oxygen is required for the decay of this additional organic matter. Oxidation of phosphorus consumes 140 grams of oxygen for each gram of phosphorus oxidized (Stumm and Morgan, 1981). The depletion of dissolved oxygen from the water column is undesirable as a certain oxygen level is required by fish and other aquatic biota to sustain life.

3.2 Phosphorus in Hamilton Harbour

Hamilton Harbour has a number of major phosphorus sources, including the Woodward Ave WWTP, Skyway WWTP, combined sewer overflows (CSOs), and runoff delivered to the Harbour via Cootes Paradise and the major tributaries. While the annual load of phosphorus to the Harbour is a challenge in itself to estimate, this is complicated by the observation that relatively higher phosphorus concentrations in summer may be due to sewage loads entering the epilimnion during stratification (Charlton, 2001).

The Hamilton Harbour beneficial use impairments (BUIs) related to excess phosphorus are: degraded fish and wildlife populations (indirectly through DO issue), degradation of benthos (indirectly through DO issue), eutrophication or undesirable algae, degradation of aesthetics, degradation of phytoplankton and zooplankton (indirectly through DO issue), loss of fish and wildlife habitat (indirectly through algal induced reductions in water clarity).

Because water clarity and a hypolimnetic dissolved oxygen deficit (eutrophication) were concerns for Hamilton Harbour during the development of the Hamilton Harbour RAP, a reduction in the loadings of phosphorus to the Harbour and resultant lower concentrations in the

Harbour were goals set to address these water quality concerns. Water clarity/aesthetics and hypolimnetic dissolved oxygen were both expected to be addressed through lower phosphorus loadings resulting in lower chlorophyll *a* concentrations in the Harbour. The focus in this chapter of the report is water clarity related to eutrophication and the development of the phosphorous concentration and loading goals for the Harbour. The consumption of dissolved oxygen by eutrophication and the potential for the Harbour to meet the DO final goal of 4 mg/L is discussed in greater detail in the dissolved oxygen chapter.

3.3 Historical Recounting of Phosphorus Goal and Target Decisions

As is implied by the complexity involved in reconstructing the phosphorus concentration and loading targets, internal discussions at historical RAP meetings played a key role in setting the initial and final eutrophication-related targets for Hamilton Harbour. During the early development of the RAP goals, the Technical Team was juggling various model scenarios, how to treat Halton and Hamilton equitably, the realization that discharge to the lake removed a large ‘hydraulic’ component to the flushing of the Harbour, and the potential cost of various possible treatments at the Woodward WWTP (K. Rodgers, personal communication, 2007). While the TP initial and final goals of 34 and 17 µg/L can be related to a particular model outcome (as will be discussed), the environmental goals related to chlorophyll *a* concentrations (15-20 µg/L initial, 5-10 µg/L final) and Secchi disc depth (2.0 m initial, 3.0 m final) are ‘rounded-off’ and emerged through a consensus on what was desirable and/or achievable targets for the Harbour using various model scenario outcomes as a guide.

Different components of the initial and final eutrophication goals for Hamilton Harbour were built upon the use of many different environmental models and relationships, which at times demonstrate inconsistency in results between one another. Uncertainty is a large component of modelling, especially when based upon a very complex environmental system such as Hamilton Harbour; this uncertainty should be kept in mind when evaluating the role these various models played in the selection of RAP goals and targets. A model is only one tool of many that can be used, and was used to make management decisions about the remediation of Hamilton Harbour.

Initial Concentration Goal of 34 µg/L

The initial goal of 34 µg/L was based primarily on work in the HH RAP (1987) and subsequently the MMM (1988) report that indicated this value as a predicted Harbour concentration that corresponds to a reduction of TP Harbour loadings of 62% (MMM, 1988) or 163 kg/d (HH RAP, 1987). This reduction was estimated to be possible through construction of CSO retention basins/elimination of CSOs, WWTP upgrades to sand filters, and a 50% reduction in TP from urban runoff/creeks (i.e. non-point sources). In addition, a cost-effectiveness study in the MMM (1988) report indicated that the preferred scenario for addressing an adequate water quality improvements (i.e. increased water clarity) in the Harbour to support a warm water fishery (Northern Pike habitat) was the installation of sand filters at Woodward Avenue WWTP. Central to determining Harbour conditions under these various management scenarios in the

MMM (1988) report was the Snodgrass and Ng (1985) model, however, the 34 µg/L was predicted based on relationships presented in HH RAP (1987)², which are also likely derived from Snodgrass and Ng (1985).

Complicating matters, a scenario analysis is presented in MOE (1985) that predicts a Harbour TP concentration of 34 µg/L which corresponds to scenarios where effluent from the Woodward WWTP is 0.1 mg/L (expected phosphorus concentration at a level of treatment beyond sand filters); this modelling work is based on the OECD (1981) Janus-Vollenweider model, and is inconsistent with the scenario predicted in HH RAP (1987) and MMM (1988). Both possibilities on the source of 34 µg/L indicate that the feasibility of remedial actions were determined prior (or concurrently) relative to desired TP Harbour concentrations and associated environmental conditions, i.e. a reduction in the TP effluent concentration at Woodward Ave WWTP from sand filters and/or dual point injection was determined to be a priority. The choice of 34 µg/L as a Harbour initial TP goal is based on the HH RAP (1987)/MMM (1988) work relative to the MOE (1985) work and the selection of this value/scenario in the MMM (1988) cost-effectiveness study.

Final Concentration Goal of 17 µg/L

The final phosphorus concentration goal of 17 µg/L can be linked to a concentration of 23 µg/L through the work undertaken in regard to the impact that Harbour iron loadings have on ambient phosphorous concentrations (i.e. Discussion Document, 1988). A predicted Harbour phosphorous concentration of 23 µg/L is reduced to 17 µg/L under a scenario of significant iron loadings due to the impact that iron has on phosphorus precipitation in Harbour waters³. The phosphorous concentration of 23 µg/L was chosen based on ‘most reasonable best-case’ (i.e. not diversion) actions deemed technically feasible (phosphorous concentration reduced to 0.1 mg/L at WWTPs, 50% phosphorus reduction from creeks/non-point sources, and elimination of CSO), and as well because of the expected improvement to the DO demand (40-60%) that is due to algal decay at this particular concentration. These remedial actions, resultant phosphorus concentrations and predicted DO improvements are based on work in HH RAP (1987) and again in MMM (1988). *The model that predicted a Harbour concentration of 23 µg/L following these remedial actions is not indicated.*

The connection between the final phosphorus concentration and loading goals and an improved dissolved oxygen concentration in the Harbour is re-iterated in Recommendation

² Table 3.1 in MMM (1988) makes reference to MOE (1985) and HH RAP (1987) as the source of the data, and doesn't indicate which of the concentration/loading estimates are from which of these two previously written reports. Later follow-up by this author indicates that references to MOE (1985) in the development of phosphorous concentration targets in MMM (1988) (i.e. page 3-11), should in fact be referring to HH RAP (1987), not MOE (1985).

³ Using 1989 industrial iron loadings (1776 kg/d), a Harbour concentration of 17 µg/L would be predicted from a Harbour concentration of 22 µg/L when not considering iron loadings; Using 1987 industrial iron loadings (3270 kg/d), a Harbour concentration of 17 µg/L would be predicted from a Harbour concentration of 25 µg/L when not considering iron loadings. Final RAP work likely used 1988 iron loadings (cannot be found at this time) as the iron loads were likely between 1987 and 1989 loads, and thus a Harbour concentration between 25 µg/L and 22 µg/L; also, TSS loading targets likely used 1988 TSS loads giving credence to 1988 as an overall ‘base’ year for development of RAP goals..

4.3.11 in the Preferred Options Report (1990) which indicates that the final phosphorous loading goal of 142 kg/d is in place to meet the final DO concentration goal of 4 ppm.

Initial (330 kg/d) and Final (142 kg/d) Phosphorus Loading Targets

The process that was used to develop both initial and final TP loading targets based on the desired initial and final TP concentrations is largely based on the Janus-Vollenweider OECD (1981) model, applied specifically to Hamilton Harbour in a memorandum by Janus (1987). The RAP literature indicates that the iron-modified Janus-Vollenweider (1981) regression equation more accurately predicted Harbour TP concentrations (Discussion Document, 1988), and was thus used in the development of the final Harbour TP goal of 17 µg/L from an original target of 23 µg/L (HH RAP, 1987; MMM, 1988).

*Initial Chlorophyll *a*, Secchi disc depth and Aquatic Plant area Targets*

Although the rationale for the initial chlorophyll *a*, Secchi disc depth and aquatic plant area targets is not made explicit in RAP documents, it is reasonable to suppose that they were anticipated to correspond with interim water quality and loading targets for suspended sediment and phosphorus.

*Final Chlorophyll *a*, Secchi disc depth and Aquatic Plant area Targets*

The final chlorophyll *a*, Secchi disc depth and aquatic plant area targets were based on the work of Painter et al. (1990). In Painter et al. (1990), modelling results are described that were undertaken from the perspective of evaluating potential water clarity improvements in Hamilton Harbour for beneficial uses related to swimming and increasing fish habitat. The model results indicate that at a phosphorous loading of 134 kg/d, chlorophyll *a* concentrations could potentially be reduced to 5 µg/L, the Secchi disc transparency could possibly increase to 3m and aquatic plant distributions could increase to 170 ha. Figure 5 in Painter et al. (1990) shows regressions between Secchi disc depth and phosphorous loading, and chlorophyll *a* concentrations and phosphorous loading, meaning a target phosphorous loading was developed based on a desired chlorophyll *a* concentration, not a desired phosphorous concentration. The regressions in Figure 5 (Painter et al., 1990) are consistent with their results indicated.

A phosphorus loading of 134 kg/d for water clarity targets is very close to the RAP final phosphorus target of 142 kg/d, which was developed from a feasibility and DO perspective. As such, it is likely that because these two exercises produced such similar phosphorous loading recommendations, the management plans for meeting both the DO and water clarity targets were joined in the selection of 142 kg/d as a final phosphorous loading target.

Summary

The RAP team's selection of final and initial phosphorous concentrations of 23 µg/L (i.e. 17 µg/L with iron-loadings) and 34 µg/L, respectively were based on achievability/feasibility and use of best available technology at the WWTPs (HH RAP, 1987). The initial phosphorous

concentration goal was also selected for its potential in increasing water clarity to the point of providing enough Northern Pike habitat to support a warm water fishery (MMM, 1988). The final phosphorous concentration goal was also selected for its potential to achieve the final DO target through reduced algal growth and subsequent oxygen consumption through algal decay (HH RAP, 1987).

The final phosphorous loading goal was set to address both the DO (concentration in HH RAP, 1987, input to Discussion Document, 1988; Vogt, 1988; Preferred Options Report, 1990) and water clarity (Painter et al., 1990) issues in the Harbour.

Further details and interpretation on the historical development of RAP concentration and loading goals pertaining to phosphorous are described in Sections 3.3.1 to 3.3.14.

3.3.1 MOE (1985)

The relationship between phosphorus concentrations in Hamilton Harbour and the undesirable impacts of eutrophication have been studied for some time and pre-date the development of the RAP documents. In MOE (1985), the results of several empirical models were discussed as to predicted chlorophyll *a* concentrations in Hamilton Harbour under different phosphorus loading scenarios (p.84). The results of three models are investigated: Janus and Vollenweider (1981), Chapra and Dobson (1979) and Dillon and Rigler (1974); the first of these predicted *annual* average chlorophyll *a* concentrations while the latter two predicted average *summer* chlorophyll *a* concentrations. MOE (1985) indicated that looking at average *summer* chlorophyll *a* concentration may be of greater relevance due to impacts more heavily felt during this part of the year, such as complaints due to aesthetics and hypolimnetic dissolved oxygen deficit. However, it was found that the Janus-Vollenweider (1981) model predicted the average annual chlorophyll *a* concentration close to the observed value, while the other two models over-predicted the average summer chlorophyll *a* levels. The models that used the favoured averaging window (summer chlorophyll *a* concentrations) also had the poorest record in predicting Harbour response.

Ten phosphorus loading scenarios were investigated as shown in Table 4 below, and focused solely on potential changes in phosphorus loads from the Hamilton STP (Woodward Ave WWTP) as its contribution to total Harbour load was and continues to be dominant. It is not clear why at the 0.1 g/m³ effluent TP concentration, the Harbour TP concentration remains at 34 mg/m³ for the Janus-Vollenweider model despite increasing flow at the plant. This indicates that at this effluent TP concentration, flow increases at the Woodward Avenue WWTP were predicted to have negligible impacts on Harbour TP concentrations when averaging with all other Harbour TP sources. This demonstrates how a concentration of 0.1 g/m³ TP in effluent is a critical concentration for Woodward Avenue WWTP. The corresponding Harbour concentration of 34 µg/L would therefore also be a critical concentration as it represents a best case Harbour TP concentration when Woodward Avenue WWTP is using best available technology for TP control, at a range of realistic current and future flow rates.

While 34 µg/L is the initial phosphorus concentration goal for the Harbour, and the modelling exercise outlined in MOE (1985) may have contributed towards the later selection of 34 µg/L as the initial phosphorus goal, the selection of 34 µg/L has its roots in the modelling exercise described in HH RAP (1987). It should also be noted that the dataset and one model used (Janus- Vollenweider model) in MOE (1985) predicted *the average annual Harbour phosphorus concentration to be 27 µg/L even with all direct discharges removed*. Although this describes only one dataset and model scenario, it is noteworthy in that the final phosphorus Harbour target concentration is 17 µg/L, emphasizing the potential impact that different datasets and models can have on predicted outcome.

Table 4: Phosphorus Loading scenarios investigated in MOE (1985, p.96); all loading scenarios refer to flow and TP concentration changes at the Woodward Ave WWTP (except last scenario)

Loading Scenario - flow and [TP]	Description	Calculated STP loading at flow and concentration specified (kg/day)	Ave. loading [TP] (mg/m ³) all sources including L. Ont- (conc. corrected for residence time)*	Janus –Vollenweider model		Chapra-Dobson model	Dillon-Rigler model
				Predicted ave. <i>annual</i> [TP] (mg/m ³)	Predicted ave. <i>annual</i> [chl] (mg/m ³)	Predicted ave. summer [chl] (mg/m ³)	Predicted max summer [chl] (mg/m ³)
250 x 10 ³ m ³ /d 1.0 g/m ³	Base Case - 1982 hydraulic flow and effluent [TP] from Woodward Ave WWTP	250	109 (73)	60	15	18	28
250 x 10 ³ m ³ /d 0.5 g/m ³	Flow (Basecase) Conc (reduced)	125	86 (57)	48	10	13	20
250 x 10 ³ m ³ /d 0.1 g/m ³	Flow (Basecase) Conc (reduced)	25	66 (44)	34	8	8	12
400 x 10 ³ m ³ /d 1.0 g/m ³	Flow Conc (basecase)	400	114 (76)	69	17	24	34
400 x 10 ³ m ³ /d 0.5 g/m ³	Flow Conc	200	92 (61)	51	12	17	22
400 x 10 ³ m ³ /d 0.1 g/m ³	Flow Conc	40	64 (43)	34	8	8	12
550 x 10 ³ m ³ /d 1.0 g/m ³	Flow (planned hydraulic expansion) Conc (Basecase)	550	149 (99)	80	19	29	42
550 x 10 ³ m ³ /d 0.5 g/m ³	Flow (planned hydraulic expansion) Conc (reduced)	275	102 (68)	55	13	18	24
550 x 10 ³ m ³ /d 0.1 g/m ³	Flow (Planned hydraulic expansion) Conc (reduced)	55	65 (43)	34	8	8	12
All direct discharges removed	No STP loading		43 (29)	27	6	7	9

Notes:

*For column 4, the average TP loading concentration was calculated based on the following equation:

$$[\text{average TP loading in mg/m}^3 \text{ or } \mu\text{g/L}] = (\text{total Harbour TP loading in kg/d}) / (\text{total flow to Harbour "Q" in m}^3/\text{d})$$

Where:

Q is assumed = $3.07 \times 10^6 \text{ m}^3/\text{d}$ based on a Hamilton Harbour residence time of 0.25 year, or $0.65 \times 10^6 \text{ m}^3/\text{d}$ based on Harbour residence time of 1.18 year
(outlined in Janus, 1987)

The concentration corrected for residence time is based on the following equation (from Environment Canada, 1981):
= [average TP loading in mg/L] / (1 + sqrt (Tw))

For column 5, the predicted average annual TP concentration is predicted based on the equation (from Environment Canada, 1981):

$$\text{Log [P}_a\text{]} = 1.229 * \log ([\text{P}_b] / (1 + \text{sqrt (T}_w)))^{0.883}$$

Where:

TP_a = predicted average Harbour TP concentration in mg/L,

TP_b = average TP inflow concentration to Harbour in mg/L

assumed = (total TP Harbour loading) / (total flow into Harbour or "Q"), where $Q = 3.07 * 10^6 \text{ m}^3/\text{d}$ based on assuming 0.25 year Harbour residence time)

T_w = Harbour residence time (assumed 0.25 year)

3.3.2 Snodgrass and Ng (1985)

Snodgrass and Ng (1985) explored several management strategy scenarios for Hamilton Harbour in order to address the hypolimnetic dissolved oxygen deficit. Although these scenarios are discussed in more detail in the dissolved oxygen chapter, it should be noted here that several of these scenarios discussed loading reductions of various phosphorus sources. For instance, in the most stringent of scenarios examined, an 80% reduction in soluble reactive phosphorus from the WWTPs and a 50% reduction in biologically available phosphorus from diffuse sources were explored. The Snodgrass and Ng (1985) model *may* have been used to derive the initial (34 µg/L) and final (23 µg/L, later converted to 17 µg/L) phosphorous concentration targets which are outlined in HH RAP (1987). The text in HH RAP (1987) does not provide context of how these concentration targets were calculated, but there is some similarity between the scenarios described in HH RAP (1987) and Snodgrass and Ng (1985).

Points of note from Snodgrass and Ng (1985) are:

- management strategies described in Snodgrass and Ng (1985) were intended to be undertaken concurrently with other strategies (i.e. reduction in SOD and NH₃); this recommendation may have been acted upon as it is believed the final ammonia target was also derived from Snodgrass and Ng (1985);
- reductions of specific forms of phosphorus from various sources are described; this recommendation may not have been directly acted upon but is discussed in a later section – “Revisiting and Updating of Historical Methods Used to Determine Phosphorus Loading Targets”.

3.3.3 HH RAP (1987)

The HH RAP (1987) report outlined key problems in Hamilton Harbour, and some early modelling estimates on the potential for improved environmental conditions in the Harbour following various remedial actions. *Both the initial and final RAP TP target concentrations are discussed in this report.* This report indicated that a 70% reduction in (1985) phosphorus loadings to the Harbour would result in a 50% biomass reduction, and would result in large improvements to Harbour conditions. The 70% reduction was deemed possible through “heroic” treatment measures at the STPs, a 50% reduction of phosphorus in all streams (an optimistic assessment of the real potential) and an elimination of all the CSOs to the Harbour. The downfall of this plan was that it left no buffer for population expansion because even with STP upgrades (improvements to effluent phosphorus concentrations), the flows would increase. The preferred remedial action by the writers of the report was diversion of STP effluent to Lake Ontario, however, this report made it clear that RAP Stakeholders had rejected this proposal on principle.

The fact that the HH RAP (1987) report was not entirely supportive of the ability of phosphorous load reductions to control primary production in the Harbour underlies the current challenge in relating the TP concentration targets to water clarity goals. Phosphorus control was expected to reduce peak algal blooms, but not the production level, and hence little impact on the dissolved oxygen and water clarity issues (p.9). This is reinforced by the recurring statement that algal growth in the Harbour is not limited by phosphorus, and hence loading reductions were expected to have little noticeable improvement in water clarity (p.26).

Phosphorous loading targets and predicted Harbour phosphorous concentrations were discussed under the section “Sediment Oxygen Demand Reduction” and “Other Factors Affecting Rehabilitation of Fishery”, implying that reductions in phosphorus loadings were primarily considered as a means to improve hypolimnetic dissolved oxygen concentrations and the fishery, not just water clarity. It appears that both the Snodgrass and Ng (1985, as described above) and HH RAP (1987) models were used to predict Harbour phosphorus concentrations under various scenarios in forming the initial and final TP concentration targets, since desirable concentration targets of both 34 µg/L and 23 µg/L (i.e. 17 µg/L with iron-modification) are discussed. *Having the target phosphorus concentration developed for addressing the dissolved oxygen demand, and the chlorophyll a/Secchi disc depth/aquatic plant area developed for addressing water clarity (see Painter et al., 1990), may be why the inconsistency in the results of these two modelling efforts (e.g. predicted Secchi disc depth under proposed phosphorous loading scenario) was acceptable during RAP targets/goals development.* It is likely that the modelling carried out for HH RAP (1987) and Painter et al. (1990) were for these two streams of desired outcomes (DO and water clarity, respectively), and because the phosphorus loading required to reach the agreed-upon/common final goal was similar between the two streams (HH RAP, 1987 indicated 23 µg/L, which translates to 142 kg/d with an iron-modified Harbour concentration of 17 µg/L using OECD, 1981 work; Painter et al., 1990 indicated a required phosphorous loading of 134 kg/d), a single final phosphorus loading goal of 142 kg/d was set for both streams of work.

Nonetheless, the scenarios and resulting conditions outlined in HH RAP (1987) are as follows (pages 26-28):

- Average phosphorous concentration in Harbour of 34 µg/L, through phosphorous loading reduction to 163 kg/d deemed possible by: implementation of best available technology at point sources (installation of filters) and reducing non-point loadings by 50%⁴. This was expected to have little noticeable improvement in water clarity, and little reduction (between 15 and 34%) in annual algal growth, which was not on the scale required to reduce the internally generated oxygen demand resulting from algal growth to a desirable DO level in Harbour waters. The target RAP phosphorous loads to reach this concentration, however, were re-calculated based on OECD Janus-Vollenweider relationships.

⁴ Note that the scenario that predicts a Harbour concentration of 34 µg/L in HH RAP (1987) is different than the scenario described in MOE (1985), which also predicts a concentration of 34 µg/L

- Average phosphorous concentration in Harbour of 23 µg/L, through phosphorous loading reduction to 89 kg/d deemed possible by: reducing STP phosphorous concentration effluent to 0.1 mg/L, 50% reduction in creek inputs and elimination of CSOs. This was expected to improve water clarity (Secchi disc depth readings of 1.5 to 2 m) and reduce internally generated oxygen demand by 40 to 60%⁵. It should be noted that 23 µg/L converts to 17 µg/L using the iron-modified regression as outlined in the Discussion Document (1988), and thus *this scenario likely describes the derivation of the final target of 17 µg/L*, and the resulting environmental conditions in the Harbour. The target RAP phosphorous loads to reach this concentration, however, were re-calculated based on OECD Janus-Vollenweider relationships.
- An average phosphorus concentration in Harbour of 19 µg/L, through phosphorous loading reduction to 50 kg/d was deemed possible by: diversion of STP effluent to Lake Ontario, elimination of CSOs and reduction of creek inputs by 50%. This was expected to result in a very noticeable improvement in water clarity (Secchi disc depth readings of 2 to 2.5 m) and a reduction in the internally generated oxygen demand by 70%. *It should be noted that the predicted Harbour phosphorous concentration of 19 µg/L under modelling efforts undertaken towards HH RAP (1987) is inconsistent with the value obtained in modelling efforts undertaken towards MOE (1985), as this latter report predicted a Harbour phosphorous concentration of 27 µg/L with all direct discharges to the Harbour removed (i.e. diversion).* The MOE (1985) report made use of the OECD (1981) Janus-Vollenweider work, while it is believe the HH RAP (1987) report used the Snodgrass and Ng (1985) models to generate described results.

3.3.4 Janus (1987)

A memorandum by Janus (1987) was written to establish how Hamilton Harbour monitoring data compares to OECD eutrophication relationships presented in Janus and Vollenweider (1981). This early work by Janus (1987) established that Hamilton Harbour generally follows the OECD standards for water quality relationships in lakes. OECD standards are based on established relationships between total phosphorus, chlorophyll *a* and Secchi transparency for a number of different international lakes. Knowing that Hamilton Harbour can be described by these developed relationships simplifies work that needs to be undertaken to reach a decision on what the required water quality parameter concentrations should be to reach desired environmental conditions.

Janus (1987) indicated that using the OECD model, TP in Hamilton Harbour is underestimated either due to high flushing rate (likely through Lake Ontario exchange) and/or high sedimentation rate (likely due to iron loadings from the steel mills). Despite this, it was

⁵ A reduction of DO demand by 40-60% may equate to a hypolimnetic DO concentration of 3.5 mg/L. Snodgrass and Ng (1985) predict 3.5 mg/L minimum hypolimnetic DO under a similar scenario and p.179 in the Stage 1 Report (1992) indicates an oxygen concentration of 3.5 mg/L from a phosphorous loading reduction to 100 kg/d.

also concluded that as additional decreases in loading were undertaken, lower phosphorus concentrations in the Harbour would result. Lower ambient phosphorus concentrations were expected due to observed Harbour phosphorus concentrations that responded to loading changes in a manner that was predicted by established OECD relationships. It was also determined that TP controls chlorophyll *a* concentrations on an annual basis, and that nitrogen does not.

3.3.5 Marshall Macklin Monaghan Limited (1988)

The Marshall Macklin Monaghan Limited (1988) report (MMM, 1988) was prepared for the Ontario Ministry of the Environment in April 1988 to “[identify] remedial and mitigative measures for achieving various proposed uses in specified areas for Hamilton Harbour and [develop] a framework for valuing the benefits associated with the resulting improvements in water quality and recreational activities” (p.i, MMM, 1988). The report was written following a cost-effectiveness framework, where scenarios were preferred when a major change in water quality was expected for a small increment in cost. Analysis included in parts of the report played a large role in the development of RAP goals and targets, although the report as a whole was not used to independently guide the RAP process due to stakeholder opposition to the report when released (K. Rodgers, personal communication, 2007).

The early development of Harbour phosphorus concentration and loading targets necessary to meet desired outcomes for the Harbour, are presented in Table 3.1 of the MMM (1988) report. Portions of this table relating to Harbour phosphorus targets and outcomes are presented in Table 5 below, and are based on work undertaken towards and presented in HH RAP (1987)⁶. As indicated under the *remarks* column, a Harbour concentration of 34 µg/L was predicted after implementation of CSO retention basins, WWTP upgrades to sand filters, and a 50% reduction in phosphorus from urban runoff/creeks. Page 3-11 of the MMM (1988) report indicates that this concentration of 34 µg/L is achievable though a reduction of the TP loadings to the Harbour by 62%, and that the proposed TP management actions do not take into account any future increased sewage flow which will contribute to phosphorus loadings.

Also indicated under the remarks column, a Harbour concentration of 23 µg/L was predicted after implementation of CSO retention basins (95% reduction of CSOs), WWTP upgrades to sand filters *plus dual point chemical injection*, and a 50% reduction in phosphorus from urban runoff/creeks. Page 3-11 of the MMM (1988) report indicates that this concentration

⁶ In the text of the MMM (1988) report (e.g. page 3-11), MOE (1985) is given as the reference for the development of 23 µg/L and 34 µg/L, however, it is believed these values were based on assessments outlined in HH RAP (1987) as: a) Table 3.1 in MMM (1988) makes reference to HH RAP (1987) as a source of this data (in addition to MOE, 1985); b) scenarios similar to those outlined in MMM (1988) cannot be found in MOE (1985) (and MOE, 1985 does specifically consider increases to sewage flows); and c) scenarios outlined in MMM (1988) are very similar to those described in HH RAP (1987).

of 23 µg/L is achievable through a reduction of the TP loadings to the Harbour to 89 kg/d. *A Harbour total phosphorous concentration of 23 µg/L becomes 17 µg/L when applying the iron-modified equation described in the Discussion Document (1988) to 23 µg/L with late 1980s industrial iron loadings to the Harbour.*

Table 5: Assessment of proposed remedial action plans for Hamilton Harbour Remedial Application Measures (from Table 3.1, MMM, 1988)

Remedial Measure	Source	Remedial Action to Loadings – Phosphorus reduction (kg/d)	Remarks
Retention basins	CSOs	78* to 5	-\$5 million for the initial phase (completed in 1987) of the 26 CSOs
Sand Filters	Hamilton WWTP	220 to 93	Above Phosphorus measures (Retention basins, filters & decreased runoff) expected to produce a Harbour water concentration of 34 mg/m ³ as compared to a PWQO value of 20 mg/m ³
	Burlington WWTP	47* to 20	
-More stringent controls on construction runoff -minimize peak stream flows -change farming practices	Storm runoff/ Creeks	80* to 40 (reduce by 50%)	
Dual Point chemical injection	Hamilton WWTP	93 to 31	Above Phosphorus measures plus dual point chemical injection expected to produce a Harbour water concentration of 23 mg/m ³
	Burlington WWTP	20 to 7	
Discharge directly to Lake Ontario	Hamilton WWTP		Direct discharge of STP's to Lake Ontario + retention basins & reduced runoff expected to produce water P conc. meeting PWQO
	Burlington WWTP		

*loadings confirmed as 1985 phosphorus loadings as indicated on p.128 of Discussion Document (1988); note that 1985 Hamilton STP loadings in Discussion Document (1988) are indicated as 399 kg/d

Notes: The sources of information for this table in the MMM (1988) report are indicated as: MOE (1985) and Rodgers et al. (1987); Rodgers et al. (1987) should be referenced as HH RAP (1987)

Harbour TP concentrations of 34 µg/L and 23 µg/L (i.e. 17 µg/L) are the initial and final phosphorus concentration goals for Hamilton Harbour, and thus if derived from the MMM

(1988) report (based on HH RAP, 1987), these values were partially selected based on feasibility of actions necessary to meet this goal. The beneficial secondary impacts of meeting 34 µg/L and 23 µg/L were related to a reduction in annual algal growth and a corresponding reduction in oxygen demand, as (quantitatively) described in HH RAP (1987).

The sum of the proposed loadings under the 34 µg/L Harbour concentration scenario from the two WWTPs (93 + 20 kg/d), streams (40 kg/d) and CSOs (5 kg/d) is 158 kg/d, which is not consistent with the initial RAP phosphorus loading goal of 330 kg/d. This may be because the iron-modified equation (Discussion Document, 1988) was used to derive the loading value based on a desired concentration of 34 µg/L; the realization of the impact of iron loadings on Harbour phosphorous concentration allowed a higher phosphorus loading goal than specified in HH RAP (1987) and MMM (1988). The CSO target of 5 kg/d is however the final RAP loading goal for CSOs, as it was likely determined that completion of the retention basins is a best case scenario.

After discussion on the potential phosphorus management strategies and predicted outcomes as taken from HH RAP (1987), the MMM (1988) report goes into detail on the outcome of their cost-effectiveness study⁷. The study quantified mitigative measures in terms of relating monetary cost of each mitigative measure, to benefits expressed as improvements in water quality (dissolved oxygen in the hypolimnion) and increment in littoral habitat for a warm water fishery.

Predicted loading concentrations for the Harbour from various mitigative measures were input into the Snodgrass and Ng (1985) nutrient-plankton biomass eutrophication model (p.3-23, MMM, 1988). A Monte Carlo simulation was performed using a range of expected loadings for each mitigative scenario (Table 3.11, MMM, 1988), and the calculated Secchi disc depth was adapted/modified (for use of extinction coefficients) from that used in the model as outlined on page 3-34. All mitigative options for phosphorus control were analyzed in terms of how they supported a warm water fishery in Hamilton Harbour, using Northern Pike as an example species. The eutrophication model links total external phosphorus loadings to the total phosphorus concentration in the Harbour, which determines chlorophyll *a* concentration, and subsequently Secchi depth, % Harbour suitable for macrophytes to grow, and finally yield of northern pike. *Thus, yield of northern pike in Hamilton Harbour was the variable used to evaluate phosphorus loading mitigative measures for Hamilton Harbour*, as outlined in Figure 3.1 of the MMM (1988) report. As northern pike prefer warm littoral regions of epilimnetic waters, white fish were used to evaluate “water quality” (hypolimnetic DO) outcomes in the

⁷ The MMM (1988) report indicates differences between the MOE (1985) modelling and MMM (1988) eutrophication modelling occur due to non-linearities considered in the MMM (1988) modelling which are not considered in the MOE (1985) model predictions (p.3-12, MMM, 1988). This may be an artefact of the MMM (1988) report continually referencing MOE (1985) instead of HH RAP (1987) as the source of 23 µg/L and 34 µg/L, as it is believed that HH RAP (1987) used the Snodgrass and Ng (1985) model to develop 23 µg/L and 34 µg/L, which does consider non-linearities in processes, and is the same model used in MMM (1988). This is likely why the scenario outcomes between HH RAP (1987) and MMM (1988) are similar despite the (unnecessary) caveat provided by MMM (1988)

Harbour. “[A] warmwater fishery was identified by the Stakeholders at the Initiation Meeting of September 1, 1987, as a use with which everyone was in general agreement as a priority use” (p.3-24 of MMM, 1988). Adding to this as outlined in the executive summary – “[t]he preferred end use favored by the Stakeholders and used in this study was a self-sustaining edible fishery” (p.i, MMM, 1988).

There were 18 control measures (i.e. scenarios) investigated for phosphorus control and the order on which they were evaluated was based on the cumulative annual cost 10 year amortization for each measure; (Table 3.9d, MMM, 1988). The least expensive control was base case (1984-1985 loadings and limnological conditions) while the most expensive was discharge to Lake Ontario; sand filters and dual point injection at the Hamilton and Burlington WWTPs were control numbers 9-12 and thus mid-range. The results of the cost-effectiveness study on restoration of littoral fish habitat indicated three distinct sections or groups on the cost-effectiveness curve: options 1 to 8; options 9 to 13, and options 14 to 18. Options 9 to 13 (initiation of phosphorus controls) had a marked improvement over Options 1 to 8 in terms of improvement to littoral habitat. Because improvements to habitat within this group were similar (~40-45% improvement in percent of habitat) but options differed in terms of monetary cost, *option 9 was preferred as it was the least expensive option to achieving this level of habitat improvement. Option 9 corresponded to the implementation of sand filters at the Hamilton WWTP; Table 5 above links the installation of sand filters at the Hamilton WWTP (among other remedial measures) to a Harbour TP concentration of 34 µg/L.*

When examining the predicted concentrations for various water quality parameters (nitrate, organic nitrogen, soluble phosphorus, total phosphorus, chlorophyll *a*, extinction coefficient) based on the 18 Options, in many cases, Option 9 corresponded to the option where a significant water quality change was predicted to occur, thus indicating the key role of this remedial measure. Figure 3.8i indicates the predicted maximum total phosphorus concentration in the epilimnion during summer for each control measure scenario; Option 9 corresponds to a TP concentration of ~32 µg/L (error bars encompass ~29-35 µg/L). The initial TP concentration target for the Harbour is 34 µg/L. Figure 3.8k indicates the predicted chlorophyll *a* concentration in the epilimnion during summer for each control measure scenario; Option 9 corresponds to a chlorophyll *a* concentration of ~12 µg/L (error bars encompass ~8-15 µg/L). The initial chlorophyll *a* concentration target for the Harbour is 15-20 µg/L. Figure 3.8m indicates the extinction coefficient in the epilimnion during summer for each control measure scenario; Option 9 corresponds to a maximum extinction coefficient of ~1.25 (error bars encompass ~1.15-1.35). Using the relationship on p.3-24 of the MMM (1988) Report, this corresponds to a Secchi disc depth of ~1.3 m; the initial Secchi disc depth goal for the Harbour is 2.0 m. It should also be noted that the RAP targets related to water quality retain the connection to fish habitat as there are initial and final aquatic plant area targets for the Harbour of 105 and 170 ha respectively. The development of potential fish yield based on improvement in littoral habitat under various eutrophication scenarios is discussed in Appendix F of the MMM (1988) report. This discussion states the improvement to habitat seen under options 9 and 14, that being the implementation of sand filters at the Hamilton WWTP and retention basins for CSOs, respectively.

The initial RAP phosphorus loading goal is 330 kg/d, which is within the range provided for controls 9 to 13; the final RAP phosphorous loading goal is 142 kg/d, which is within the range provided for control 18 (discharge to Lake Ontario) as outlined in Table 3.11 of the MMM (1988) report.

3.3.6 Vogt (1988)

A memo written by Vogt (1988) describes a predicted oxygen budget for the Hamilton Harbour hypolimnion assuming steady state conditions with no sediment oxygen demand; this was done to investigate expected oxygen levels in the hypolimnion following abatement actions. This oxygen budget also assumes that effluents stay in the epilimnion and uses a chlorophyll *a*-oxygen depletion relationship developed by Charlton. Due to the nature of these assumptions, the predicted oxygen concentrations are not considered conservative.

Results indicate that by reducing the phosphorus loading to 240 kg/d as well as reducing ammonia inputs (concentration in STPs <3 mg/L to prevent spring ammonia build-up), oxygen concentrations in the hypolimnion would be maintained above 4.8 to 5.8 mg/L once historical bottom sediments are stabilized (i.e. zero sediment oxygen demand). The phosphorous loading of 240 kg/d was explained as attainable through either of two scenarios: 1) STP effluent reduced to 0.5 mg/L, eliminate CSOs, creek loadings halved; 2) STP effluent reduced to 0.45 mg/L, eliminate CSOs, no change to creek loadings⁸. It should be noted that the phosphorus reductions described in scenario 1 are similar to the scenario described in MMM (1988) that predicts a Harbour concentration of 34 µg/L following these measures. Thus, the Vogt (1988) memo ties phosphorus loading targets to the targets related to dissolved oxygen, which may have placed weight on the selection and implementation of this particular scenario as it demonstrated the achievability of both the water clarity and DO Harbour targets.

3.3.7 Discussion Document (1988)

Various improvements to Hamilton Harbour water clarity and hypolimnetic DO are outlined in the Discussion Document (1988, p.8, p.164), mostly based upon the feasibility of reductions from various phosphorous sources (p.146). Scenarios are described including installation of sand filters at the STPs, a 50% reduction in phosphorus loadings from creeks and elimination of CSOs; these scenarios are based on and described in earlier work (e.g. HH RAP, 1987; MMM, 1988; Vogt, 1988). The projected Harbour responses in terms of oxygen and water clarity (e.g. increase in Secchi disc transparency from 0.9 m to 1.3 m) were taken from MMM (1988) as specifically indicated on page 157 of the Discussion Document (1988).

The Discussion Document (1988) also described phosphorus loadings and concentrations in Hamilton Harbour, and the predicted phosphorus concentrations using the Janus-Vollenweider model for annual average concentrations. It was noted that the expected chlorophyll *a* concentrations in the Harbour are similar to other lakes around the world, provided the total

⁸ It is assumed that Vogt (1988) was referring to 1988 creek loadings.

phosphorus concentration remains below 70 µg/L (p.58), i.e. this is when OECD empirical models hold for Hamilton Harbour. The predicted phosphorus concentrations in the Harbour based on loadings were less than expected using the Janus-Vollenweider model, which was believed to be due to either flushing of phosphorus to Lake Ontario or, more likely, removal of phosphorus from the water column due to iron discharges from the steel mills. Iron facilitates phosphorus precipitation and settling of the precipitate to the bottom sediments of the Harbour. Therefore the Janus-Vollenweider model prediction was modified to account for iron inputs, which as seen in Figure 19 of the Discussion Document (1988, p.135) predicts the actual phosphorus concentration in the Harbour very well. The iron-modified model equation is (p.133 and p.145):

$$P_c = 9.4 (I + 1400)^{-0.31} P_{j-v}$$

P_c = predicted phosphorus concentration corrected for iron input

I = iron loading from the steel mills in kg/d

P_{j-v} = predicted phosphorus concentration from the Janus-Vollenweider model

It is stated that this model (iron-modified) was used to predict the phosphorus concentration in the Harbour at reduced phosphorus loading inputs (p.145).

In reference to the Janus-Vollenweider figure of total phosphorus loading versus concentration, the Discussion Document (1988) states that at a loading of 240 kg/d (see Vogt, 1988 for scenario used to derive loading), the Harbour concentration would be about 0.028 mg/L; this concentration was derived using the iron-modified Janus-Vollenweider relationship. It is also stated that if the STPs can reduce their phosphorus concentration in effluent to 0.4 mg/L, then the total Harbour loading would be reduced to 200 kg/day or 0.023 mg/L Harbour phosphorus concentration. As 0.023 mg/L or 23 µg/L was derived under the assumption of significant iron loadings to the Harbour (use of iron-modified Janus-Vollenweider relationship), conditions associated with this value as described in this context in the Discussion Document (1988) are different from those outlined in HH RAP (1987) and MMM (1988), which predict 23 µg/L under scenarios not accounting for iron loadings to the Harbour.

A summary table was provided in the Discussion Document (1988) in the context of the proposed benefit to the Harbour of certain loading reduction actions; a summary is provided in Table 6 below. The combination of the actions outlined in Table 6 below along with those for ammonia were determined to result in the following Harbour conditions: oxygen concentration in hypolimnion of >2.8 mg/L, phosphorus concentrations ~25 µg/L TP and water clarity Secchi disc >1.3 m. Resultant Harbour conditions for additional phosphorus loading reduction steps (sand filters/dual point chemical at STPs) were outlined as follows: phosphorus concentration 15-20 µg/L, oxygen concentration > 3.3 mg/L and Secchi disc transparency > 1.9 m. Figure 35 of the Discussion Document (1988, p.180) also provides a good overview of how these different parameter loading reductions were predicted to interact under various scenarios, to produce these described outcomes for the Harbour. The Harbour conditions were likely estimated from the MMM (1988) report as alluded to on p.157 of the Discussion Document (1988); these outcomes are also described in Vogt (1988) (e.g. minimum DO of 3.3 mg/L, Secchi disc transparency of

1.3 m). *Under the scenario of possible future phosphorus controls at the STPs, the range of predicted phosphorus concentration for the Harbour (15-20 µg/L) is consistent with the final RAP goal for ambient TP concentrations in the Harbour (17 µg/L); however, the other parameters are not consistent with final RAP targets due to the combination of models and work used to derive these other targets (e.g. Painter et al., 1990 for water clarity targets).* .

Table 6: Summary of Phosphorus controls and perceived benefits for Hamilton Harbour (from Table 36, Discussion Document, 1988, p.151)

Action		1987 loading (kg/d)	Reduction (kg/d)	Proposed loading (kg/d)
Hamilton STP	Chemical Precipitation – iron	292	65	
	Chemical Precipitation - primary		65	162
Burlington STP		42	12	30
CSOs		78	73	5
Diffuse source control		107	55	52
Summary of total phosphorus controls from above		519	270	249

3.3.8 Barica (1989)

Barica (1989) concluded that considering the TP loadings to Hamilton Harbour, one would expect higher phosphorus and algae concentrations in the Harbour relative to those observed. This observation has been attributed to several unique limnological factors of Hamilton Harbour, namely: short circuiting of loads through the Burlington shipping canal, iron precipitation of phosphorus, exchange of water with Lake Ontario, toxic effects of un-ionized ammonia and metals on algae, instability of the Harbour in general. These findings are consistent with the RAP's use of the iron-modified Janus-Vollenweider regression in developing Harbour phosphorus targets and goals.

3.3.9 Painter et al. (1990)

A report by Painter et al. (1990) was written following a pilot study undertaken at the Hamilton WWTP designed to assess the effectiveness of adding pickle liquor⁹ to the effluent to reduce phosphorus loading to the Harbour. This report also examined empirical and predicted relationships in water quality variables (phosphorus, chlorophyll *a*, Secchi disc depth, aquatic plant area) to elucidate the improvement in water quality observed following the pilot study in 1988. The key role of this report in the development of the RAP final water quality targets is discerned, as the predicted relationships between the water quality variables remain unchanged when examining final RAP water quality goals.

Painter et al. (1990) briefly discuss potential phosphorus management strategies for the Harbour including a reduction of 50% phosphorus loading at the Burlington STP, elimination of combined sewer overflows, and 15% reduction in soil erosion from the watershed; these measures were estimated to equate to a phosphorus loading and chlorophyll *a* concentration of 300 kg/d and 9 µg/L, respectively. Associated water quality variables expected were water clarity of 225-250 cm, and an aquatic plant distribution of 115-130 ha. While these steps would have been an improvement to Harbour conditions, it was stated that additional loading reductions were possible which could reduce the phosphorus loading to 134 kg/d and potentially lower chlorophyll *a* concentrations to 5 µg/L. Additional analysis notes that if chlorophyll *a* concentrations are reduced to less than 7 µg/L, Secchi disc transparency was expected to increase to 3 m and the aquatic plant distribution to 170 ha.

It is unclear how the phosphorus loading value of 134 kg/d was developed or what additional remedial measures were required to attain this loading, however, this value is close to the RAP final phosphorus loading goal of 142 kg/d. The value of 134 kg/d is associated with the chlorophyll *a* concentration of 5 µg/L; as further water quality predictions are based on 7 µg/L (as will be discussed), it may be that the same relationship used to equate 5 µg/L chlorophyll *a* to 134 kg/d was also used to equate 7 µg/L chlorophyll *a* to 142 kg/d total phosphorus Harbour loading. The final RAP loading target of 142 kg/d may also have been set following the modification of loading apportionment to individual Harbour loading sources, based on an original sum of sources at 134 kg/d. However, it is most likely that the loading value of 142 kg/d was derived from the selection of 17 µg/L TP as a final concentration goal, and 142 kg/d was derived based on the iron-modified Janus-Vollenweider regress at this TP concentration; 134 kg/d was likely over-ridden by this other process of setting phosphorous targets because the derived values from both processes (water clarity – 134 kg/d; DO – 142 kg/d) were so close in value.

⁹ The addition of pickle liquor (i.e. ferrous chloride - formed as a waste product during steel processing) to WWTP effluent reduces the phosphorous concentration in effluent. Iron in the pickle liquor combines with phosphorous in the effluent to form a precipitate, which can thus be removed from the effluent. Woodward Ave WWTP continues to use pickle liquor as a phosphorous removal mechanism, but plans to switch to ferric chloride in the near future.

The development of the final RAP targets for chlorophyll *a* (5-10 µg/L), Secchi disc depth (3.0 m) and submergent aquatic plant area (170 ha) as based on the work of Painter et al. (1990) is straightforward, along with the relationships that were used to join these values. In Figure 6 of the report, observed values for chlorophyll *a* concentrations versus Secchi disc depth for three Hamilton Harbour stations during the summer months of 1987-1989 are presented alongside the predicted relationships based on models by Carlson, Jones and Bachman, and OECD. All three models predict similar relationships between chlorophyll *a* and Secchi disc depth, and observed values agree well with these models. It is stated that Secchi disc transparencies of higher than 3.0 m are attainable when chlorophyll *a* concentrations are less than 7 µg/L. Due to the uncertainty surrounding 7 µg/L, this is likely why the chlorophyll *a* concentration goal was transformed into a range (5-10 µg/L) blanketed around this value.

The Secchi disc transparency of 3.0 m was expected to provide approximately 170 ha for plant colonization as deemed desirable to provide fish habitat in support of a warmwater fishery in Hamilton Harbour. The plant area of 170 ha was predicted based on the relationships between Secchi disc transparency and the maximum depth of colonization of submergent plants developed by Chambers and Kalff (1985) and Canfield et al. (1985). The hypsometric curve for the Harbour was used to predict the colonized area for any Secchi disc transparency as presented in Figure 7 of Painter et al. (1990). A value of 3 m Secchi disc depth is consistent with a value of approximately 170 ha aquatic plant area using the best fit line in this figure. It should be noted that using this Secchi disc depth-aquatic plant area relationship for a Secchi disc depth of 2 m approximates an aquatic plant area of 85 ha; therefore, *the relationships presented in Painter et al. (1990) were not used to develop the RAP initial water quality goals as the RAP initial Secchi disc depth goal of 2 m is associated with an aquatic plant area of 105 ha.*

3.3.10 Preferred Options Report (1990)

The phosphorus issue in the Harbour was addressed in the Preferred Options Report for Hamilton Harbour (1990). Table 1.1 of the Preferred Options Report (1990, p.2) listed the conditions current at the time, the impaired uses, the sources of the problem and the current information deficiencies. Phosphorus was pertinent to item #2 – eutrophication, for reasons having to do with both reduced water clarity and dissolved oxygen; this is further specified in Figure 3 of the Preferred Options Report (1990, p.5) where it is shown that phosphorus from STPs, CSOs and creeks results in too much algae, and causes poor water clarity and low oxygen (summer). The source of the problem is stated as phosphorus (and ammonia) in: STP, CSO and industrial effluent; tributary streams; sediment phosphorus reflux; and urban runoff. The relevant information deficiencies noted were the uncertain response of dissolved oxygen to phosphorus (and ammonia) reduction, and the uncertain exact loadings from storm events (CSOs and tributary streams).

The Preferred Options Report (1990) also set out initial management strategies to address the issues identified for the Harbour. Under the section on eutrophication, it is noted that embraced in the term “eutrophication” is the “excessive phosphorus loading (515 kg/d in 1987)

which promotes an abundance of algae and consequently turbid water. When the algae decay, dissolved oxygen is depleted below the provincial guideline of 4 ppm” (p.28). The eutrophication goals and anticipated ambient conditions in Hamilton Harbour pertinent to phosphorus were set out as outlined in Table 7 below; these have remained consistent to present day. It should be noted that the phosphorus loading targets and concomitant Harbour phosphorus concentrations in Table 7 below were developed using the iron-modified Janus-Vollenweider model, while the phosphorus loadings and concomitant Harbour concentrations in Table 4 were likely developed using the (non iron-modified) Janus-Vollenweider model. This may be why the TP loading-concentration relationships do not seem to be consistent between these two tables.

Table 7: Net phosphorus loading targets and environmental conditions as listed in Preferred Options Report (1990), p.30

	1987	Initial Goal (1990)	Final Goal (1995)
Objectives – Phosphorus Loading (kg/d)			
Hamilton STP	290	140	60
Burlington STP	40	30	12
Streams	95	90	65
CSOs	90	70	5
Total	515	330	142
Conditions: Hamilton Harbour			
Phosphorus conc. (µg/L)	42	34	17

As phosphorus loadings were being targeted to address both water clarity and the dissolved oxygen issue, the phosphorus management strategies in the Preferred Options Report (1990) reflected the duality of how phosphorus contributes to eutrophication issues, and were stated as follows:

Recommendation 4.3.9

THAT the initial goal of 330 kg/d for phosphorus loading be achieved by improved chemical treatment at the Hamilton and Burlington STPs. The development of the water quality model and monitoring of the Harbour’s response should be initiated at this point (Recommendations 4.3.1, 4.3.2, 4.3.3)

Recommendation 4.3.10

THAT a process audit precede all further improvements at the STPs. This would assist in designing the necessary improvements to achieve further phosphorus loading reductions (Files #1 and 4).

Recommendation 4.3.11

THAT phosphorus loadings be finally reduced to 142 kg/d (see Figure 6)¹⁰ in order to achieve a dissolved oxygen concentration of 4 ppm or greater. The installation of sand filters and dual-point chemical injection at the Hamilton and Burlington STPs will be necessary to achieve the water quality desired (File #4).

Recommendation 4.3.12

THAT diversion of STP effluent to Lake Ontario be considered only after all other technically feasible and practical options have been implemented (File #5).
(Preferred Options Report, 1990, pp.31-32)

At this point in the Preferred Options Report (1990), *it is unclear how the initial phosphorus objective of 330 kg/d was developed, but it is implied that there was uncertainty about this value and that further work should go into verifying the Harbour's response to such a loading reduction.* Discussion around the final loading objective of 142 kg/d is more specific relative to the initial loading objective; it appears that Recommendation 4.3.11 indicates that the final phosphorous loading objective was developed primarily to address the dissolved oxygen issue in the Harbour; this is consistent with work outlined in HH RAP (1987) and MMM (1988). Below Recommendation 4.3.11 in the text of the Preferred Options Report (1990), it is indicated that the final target will also improve water clarity by reducing algal abundance, and that estimated Secchi disc transparency is 3 m with the reduced loading; this is consistent with work outlined in Painter et al. (1990).

File #1 at the end of the Preferred Options Report (1990), while not going into any detail on how objectives were developed, does however indicate the expected outcome of phosphorus loading reductions. The loading reduction discussed is from 520 kg/d to 380 kg/d, which are values close to the total 1987 and initial target loadings indicated in Table 7 above. The target of 380 kg/d is said to equate to 0.5 ppm TP effluent concentration at present wastewater volumes, and was expected to increase hypolimnetic dissolved oxygen by 0.5 ppm at the end of the season from 0.7 to 1.2 ppm. This reduction in phosphorus loading was also expected to decrease mean maximum seasonal chlorophyll *a* from 18 to 11 µg/L, decrease mean maximum seasonal total phosphorus from 48 to 30 µg/L, and increase minimum Secchi disc transparency from 0.9 to 1.4 m. It should be noted that the expected phosphorus concentration of 30 µg/L under the initial loading target of 380 kg/d is again close to the value indicated in Table 7. The end of File #1 stresses the need to re-evaluate the Harbour following implementation of the specified loading reduction to ensure positive changes are in fact accomplished in the fish community structure and benthic invertebrate populations due to an increase in fish habitat and increased dissolved oxygen.

File #4 (as referenced in recommendations 4.3.10 and 4.3.11) refers to the installation of sand filters at the Skyway and Woodward WWTPs, which were considered a last step in

¹⁰ The reason for the reference to Figure 6 in Recommendation 4.3.11 is unclear as this figure is a plot of total phosphorus loadings and concentrations from 1974 – 1989. There is nothing on this figure to indicate any particular significance of the final loading target of 142 kg/d.

controlling algal growth and low dissolved oxygen if other measures did not lead to the expected Harbour response. Sand filters were expected to provide an effluent phosphorus concentration of about 0.1 mg/L, which is indicated as 1/10 of the (concentration) value in 1987¹¹. As a result, dissolved oxygen concentrations were expected to improve to the 4 to 5 mg/L levels, however, important to note is that this estimate is for when *nitrification is carried out as well*. Although not confirmed at this time, *it may be that the RAP final total Harbour phosphorus loading target was developed under the assumption that nitrification would be occurring at the STPs in order to reach the dissolved oxygen targets for the Harbour*. If this was the case, then meeting the phosphorus loading target will not achieve the desired outcomes (for dissolved oxygen) as the WWTPs are not designed for full nitrification. Meeting the final DO goal for the Harbour through reductions in both ammonia and phosphorous loadings is consistent with the recommendations provided in Snodgrass and Ng (1985). Following this, it is believed that Snodgrass and Ng (1985) played a large role in developing both the final phosphorous and ammonia loading targets, thus it seems likely that the final phosphorus loading target was developed under the assumption that nitrification would be carried out at the WWTPs in order to meet the DO final target for the Harbour.

3.3.11 Stage 1 Report (1992)

The Stage 1 Report (1992) indicated the large decreases in Harbour phosphorus loading that had occurred since the mid-1970s. The annual average phosphorus loadings to the Harbour were plotted against the annual average total phosphorus concentrations found in the Harbour, and the predicted concentrations based on the Janus-Vollenweider model (Janus and Vollenweider, 1981) are also shown (Figure 34, p.154).

Conclusions from work by Janus (1987) are reflected in the Stage 1 Report (1992), in particular the finding that the phosphorus loading-concentration model more accurately reflects actual phosphorus concentrations in the Harbour when iron inputs are taken into consideration. The iron-corrected Janus-Vollenweider model was used to predict the phosphorus concentrations in the Harbour at reduced phosphorus loading inputs (p.152).

In a later section of the Stage 1 Report (1992), it is indicated that a preliminary loading target of 200 kg/d TP for the Harbour is necessary to correct the problem of anoxia, although following this it is stated that TP loading may have to be reduced to < 100 kg/d to relieve anoxia problems (p.170). These target loadings are not in line with initial/final RAP loading targets. Figure 43 (p.179) may reflect these estimates as this figure indicates that a phosphorus loading of 290 kg/d would result in a dissolved oxygen concentration of 3 mg/L, and a loading of 100 kg/d, 3.5 mg/L¹².

¹¹ There is some inconsistency in the expected TP effluent concentration following the installation of sand filters; other documents make reference to the concentration of 0.1 mg/L TP being achievable only through dual point chemical injection

¹² This relationship between phosphorus loadings and expected dissolved oxygen concentrations is supposedly based on the work of S. Painter (1988), however, upon investigation of this reference given in the Stage 1 Report (1992),

3.3.12 Stage 2 Report (1992)

The Stage 2 Report (1992) continues the discussion started in the Stage 1 Report (1992) as it again indicates the drastic phosphorus loading reductions that had already been accomplished since the 1970s, but also indicates the improvement seen in terms of reduced chlorophyll *a* concentrations and increased Secchi depth. Again, the plot of observed Harbour phosphorus concentrations versus loads is presented against the backdrop of the predicted values using the Janus-Vollenweider model. It is re-iterated that the measured concentrations are lower than that predicted by the model, likely due to iron discharges from steel mills which acts to increase phosphorus sedimentation.

Quantitative achievable phosphorus targets are discussed in the Stage 2 Report (1992, p.63), but the loading targets discussed are not consistent with those presented in Table 7 above. The Stage 2 Report (1992) discussed municipal STP effluents being reduced to 0.5 mg/L, elimination of CSOs in Hamilton and the reduction of non-point sources by 50% to arrive at a total phosphorus loading to the Harbour of 240 kg/d; this scenario is derived from earlier work (e.g. Discussion Document, 1988, p.146; Vogt, 1988). The reader is referred to Figure 12¹³ of the Stage 2 Report (1992), and scenarios relating 240 kg/d to 0.028 mg/L, and 200 kg/d to 0.023 mg/L are described; these scenarios were presented in earlier work (Discussion Document, 1988; Vogt, 1988).

Explicit discussion on the derivation of the phosphorus loading targets and desired Harbour concentration is not provided, but from the brief scenario analysis explained above and the discussion on page 64 that indicates the need to optimize chemical treatment at the existing STPs, if not install filters, the level of available STP technology played a role in the development of phosphorus loading goals as effluent concentrations are discussed in terms of feasibility. Page 71 states that “[w]hile the current objective for phosphorus is 1 ppm concentration, the target in this plan call for a concentration of 0.10 to 0.15 ppm at current wastewater volumes”. Similar effluent concentrations are reflected in the scenario analysis provided in Table 4 of this report (as investigated in MOE, 1985).

3.3.13 McMahon and Snodgrass (1993)

McMahon and Snodgrass (1993) developed an eutrophication model to evaluate the effects of target loading reductions identified through the Hamilton Harbour Remedial Action Plan process. Because the model was undertaken post-development and setting of RAP loading and concentration targets, it was not a factor in the development of these goals; however, it is an additional tool that can be used to evaluate expected ambient conditions in Hamilton Harbour under proposed loading reductions.

dissolved oxygen in Hamilton Harbour is not discussed in Painter et al. (1998). The relationships are similar however, to those presented in Figure 35 of the Discussion Document (1988).

¹³It is believed that this should read Figure 11 in the Stage 2 Report (1992)

Three scenarios were examined: 1) implementation of the potential remedial actions proposed by the Hamilton Harbour RAP committee; 2) the effect of sand filters at the Woodward and Skyway WWTPs in addition to the changes in scenario 1; and 3) best case scenario – reduction of tributary phosphorus loadings by 95% and total phosphorus concentrations in the Woodward and Skyway WWTP effluent reduced to 0.05 mg/L.

Results for each scenario in terms of average minimum Secchi disc depth and maximum chlorophyll *a* concentration are as follows:

- Scenario 1: Secchi disc increased from 0.9 to 1.3 m; chlorophyll *a* < 20 µg/L
- Scenario 2: Secchi disc increased to 1.7 m; chlorophyll *a* ~10 µg/L
- Scenario 3: Secchi disc increased to 2.3 m; chlorophyll *a* ~7 µg/L

As loading reductions under scenario 3 are not realistic, this indicates that according to the modelling undertaken by McMahon and Snodgrass (1993), conditions in Hamilton Harbour will *likely never reach the goal of minimum 3 m Secchi disc depth* (p.62). This conclusion is not consistent with those using the OECD phosphorous – chlorophyll *a* – Secchi disc depth relationships, and demonstrates the need for further evaluation in determining if meeting phosphorus goals for the Harbour will result in desired ambient conditions relating to water clarity. Figure 7.32 in McMahon and Snodgrass (1993) shows the relationship between Secchi disc depth and total phosphorus loading to the Harbour; it is similar to the concept of the OECD phosphorous relationship curves discussed earlier but was developed specifically for Hamilton Harbour. At the initial phosphorus loading goal for Hamilton Harbour (330 kg/d), the corresponding Secchi disc depth according to the curve developed by McMahon and Snodgrass (1993) is just under 1.1 m; at the final loading goal of 142 kg/d, the corresponding Secchi disc depth is ~1.5 m. Even at a total Harbour loading of approximately 40 kg/d, the predicted Secchi disc depth is approximately 2.3 m. The modelling results by McMahon and Snodgrass (1993) are not supportive of the ability of RAP phosphorus loading targets to achieve the desired water clarity conditions in the centre of the Harbour.

3.3.14 Charlton (1997)

The Charlton (1997) paper was written to address expansion of the Skyway WWTP in the late 1990s but also addressed some very important concentration – loading relationships for Hamilton Harbour. Regardless of the method or model used to predict Harbour total phosphorus concentration, monitoring data indicated that the combined total phosphorus loadings from Hamilton and Burlington WWTPs are a primary determinant in Hamilton Harbour ambient total phosphorus concentration. The slope of the combined WWTP load – ambient Harbour concentration regression line is such that meeting the initial (170 kg/d) and final (72 kg/d) loading targets for the two WWTPs are predicted to result in Hamilton Harbour ambient total phosphorus concentrations that meet initial (34 µg/L) and final (17 µg/L) concentration targets, respectively.

Relating water quality relationships in Hamilton Harbour to OECD standards was continued by Charlton (1997) following work by Janus and Vollenweider (1981) and extended in

that expected chlorophyll *a* concentrations and Secchi transparencies were explicitly provided on the backdrop of established OECD relationships (not iron-modified concentration-loading relationship). Overlaying Hamilton Harbour data on OECD relationships of phosphorus concentrations with chlorophyll *a* concentration and Secchi transparency indicates that the Harbour should achieve desired (final target) chlorophyll *a* concentrations and Secchi disc depths at the final target ambient total phosphorus Harbour concentration of 17 µg/L.

3.4 Revisiting and Updating of Historical Methods Used to Determine Phosphorus Loading Targets

As has been demonstrated from the historical Hamilton Harbour RAP literature, the initial and final phosphorus loading targets of 330 kg/d and 142 kg/d, respectively, correspond to initial and final Harbour phosphorus concentrations of 34 µg/L and 17 µg/L, respectively, according to the iron-corrected Janus-Vollenweider regression model as is visually demonstrated in Figure 19 of the Discussion Document (1988).

In order to examine the potential need to update previously used methods used to derive the final phosphorus loading target of 142 kg/d, the equations that predicted a Harbour concentration of 17 µg/L were reconstituted based on information contained with the historical literature (Discussion Document, 1988; Environment Canada, 1981; MOE, 1985; Janus, 1987). The OECD Janus-Vollenweider equation that was used to predict average Harbour TP concentration is as follows:

$$\text{Log [TP}_a\text{]} = 1.229 * \text{log} ([\text{TP}_b] / (1 + \text{sqrt} (T_w)))^{0.883}$$

Where:

TP_a = predicted average Harbour TP concentration in mg/L,

TP_b = average TP inflow concentration to Harbour in mg/L

assumed = (total TP Harbour loading)/(total flow into Harbour or “Q”), where
Q=3.07*10⁶ m³/d based on assuming 0.25 year Harbour residence time)

T_w = Harbour residence time (assumed 0.25 year)

The above equation was based on the average of “A” and “B” regressions and the coefficients for the equation are presented on page 17 of Environment Canada (1981).

The iron-modified equation was subsequently used to correct for observed Harbour phosphorus concentrations as concentrations were less than predicted based on assumed loadings and the OECD Janus-Vollenweider equation¹⁴. It was assumed in earlier RAP documents that phosphorus concentrations in the Harbour were being underestimated either due to iron loadings

¹⁴ It remains unclear how the iron-modified equation was ultimately developed: a) literature-based; or b) empirical to Hamilton Harbour

from the steel mills that facilitated phosphorus precipitation to the sediments, or flushing losses to Lake Ontario; the RAP proceeded based on the former being the more likely assumption to explain observed Harbour phosphorus concentrations. The iron-modified equation used to predict average Harbour TP concentrations is as follows:

$$[TP_{Fe}] = 9.4 * (\text{iron loading from the two steel mills in kg/d} + 1400)^{-0.31} [TP_a]$$

Where:

TP_{Fe} = Iron modified predicted average Harbour TP concentration in mg/L

TP_a = average Harbour TP concentration in mg/L (as predicted based on OECD Janus-Vollenweider equation above)

The iron loadings used in this equation to develop RAP targets were likely from the late 1980s, as this is when the RAP targets were being developed. The iron loadings to the Harbour in 1987 were: 4070 kg/d (Harbour total loadings), 1520 kg/d (Dofasco) and 1750 kg/d (Stelco) (from Figure 29, p.133, Discussion Document, 1988); iron loadings to the Harbour in 1989 were: 1321 kg/d (Dofasco), 455 kg/d (Stelco) (Stage 1 Report, 1992).

Working backwards to verify the equations and assumptions/input values used, if using the 1987 iron loadings from industry, the predicted Harbour phosphorus concentration of 17 µg/L was based on the OECD Janus-Vollenweider equation predicting a phosphorus concentration of 25 µg/L equating to a total phosphorous loading of 153 kg/d; if using 1989 iron loadings from industry, then the Harbour concentration goal was based on the OECD Janus-Vollenweider equation predicting a phosphorus of 22 µg/L equating to a total phosphorus loading of 136 kg/d¹⁵. Substituting a loading value of 142 kg/d into the OECD Janus-Vollenweider equation yields a Harbour concentration of 23 µg/L; this value entered into the iron-modified equation yields a target Harbour concentration of 16 µg/L (using 1987 industry iron loadings) or 18 µg/L (using 1989 industry iron loadings). Thus, a loading value of 142 kg/d was likely developed based on 1988 industry iron loadings.

These results were all based on the assumption of the Harbour having a residence time of 0.25 year, however, had a longer residence time such as 1.18 year been chosen as was considered in Janus (1987), the Harbour TP target concentration would have been 59 µg/L (using 1987 industry iron loadings and the iron-modified equation) or 66 µg/L (using 1989 industry iron loadings and the iron-modified equation). The use of a residence time of 0.25 year was relatively a more appropriate choice, although it should be noted that these equations are relatively sensitive to residence time which is an uncertainty worth noting in the concentration-loading relationship.

¹⁵ A value of 136 kg/d is very close to 142 kg/d and may be within rounding error; it is possible then that 1989 iron loadings were used to develop the phosphorous loading target to Hamilton Harbour. In addition to this, Painter et al. (1990) wrote of a required total phosphorous loading of 134 kg/d (also very close to 136 kg/d), which may have played into the development of an ultimate phosphorous loading target.

These equations can be applied in the current context of the proposed TP loadings from Woodward Avenue WWTP. The final total phosphorus loading goal is 142 kg/d, with 60 kg/d apportioned to Woodward Avenue WWTP. Woodward Avenue WWTP proposed loadings at design flow are 74 kg/d (KMK, 2007), which is 14 kg/d above their final target. To understand the implications of this additional 14 kg/d, this load was added to the total Harbour TP target (14 kg/d + 142 kg/d) to yield a final TP Harbour load of 156 kg/d. Assuming a residence time of 0.25 year, the predicted Harbour TP concentration using the Janus-Vollenweider relationship is 25 µg/L at 156 kg/d, and then substituting this into the iron-modified equation yields 20 µg/L, which is the TP PWQO. However, 20 µg/L is predicted when using 1989 iron loadings, which is no longer appropriate as iron loadings to the Harbour from industry have decreased drastically since the late 1980s. Using 2002 iron loadings from industry (HH RAP, 2004), a total Harbour loading of 156 kg/d yields a Harbour concentration of 25 µg/L – the same as the OECD Janus-Vollenweider equation prediction meaning iron loadings from industry are no longer playing a role in the precipitation of phosphorus in the Harbour. Even if the 142 kg/d TP goal was met, the Harbour could only be expected to have a TP concentration of 23 µg/L (using the OECD relationships) considering the relatively small current iron loadings from industry. The 17 µg/L goal was developed on the assumption that iron loadings from industry were somewhat static. If the RAP continues to strive for 17 µg/L TP Harbour concentration goal with current low iron loadings (i.e. no longer using iron-modified equation to predict Harbour concentration from TP loading; using OECD Janus-Vollenweider equation), then the total Harbour loading would have to be 108 kg/d.

In addition to this, it is important to note that TP loadings to the Harbour from the Woodward Avenue WWTP prior to the year 2000 are believed to have been underestimated; a change was made in the year 2000 at the Woodward Avenue WWTP to an improved loading estimation method. This means that the previously established relationship between Harbour WWTP TP loadings and the resultant Harbour TP concentration has changed if reconstructed with updated loading estimates. The updated loading estimation method does however work in favour of the RAP and Harbour remediation. It means that the target Harbour TP concentration at a given TP WWTP loading value should be easier to attain relative to the pre-2000 relationship between TP in Harbour water and TP loadings from the WWTPs.

Also to be considered is if phosphorus loading/concentration targets are to be revised, what the implications are of basing targets specifically on the Janus-Vollenweider model despite some limitations of this model. Firstly, it should be noted that the Janus-Vollenweider model, as was used to develop the RAP initial and final loading goals, predicts *annual* average total phosphorus concentration and not *summer* concentrations; this was discussed in MOE (1985). The RAP has focused on a 13 week summer period for meeting the ambient phosphorus concentration, which may not be consistent with the original intent of the phosphorus concentration target for the Harbour as it was developed on a model that predicts annual averages. Seasonal variation in phosphorus loadings may also play a role in modelling the concentration-loading relationship for the Harbour as Hamblin and He (2003) surmised that phosphorus loads to the Harbour were higher in summer relative to winter.

Also, the Janus-Vollenweider work on which the loading-concentration relationships are based on, is over 25 years old. The empirical relationships developed by Janus and Vollenweider (1981) have likely changed due to impacts of climate change, invasive species (zebra mussels), etc.; how Hamilton Harbour has responded to these changes relative to regional or even global change is not known at this time. It is likely that any updates to Hamilton Harbour loading and/or concentration targets for phosphorus will need to consider these environmental changes to more realistically predict ambient Hamilton Harbour conditions under specified loading scenarios, and to determine if the target TP concentration will achieve the desired environmental conditions. This specifically includes an analysis of how zebra mussels have changed nutrient dynamics and water clarity in Hamilton Harbour, and if blue-green algae blooms are becoming more prevalent in the Harbour, and if so, why. These topics will be covered in Part 2 of this report series and will examine what the expected outcome is predicted to be following best effort potential reductions in TP loading. The RAP may have to manage expectations on what can be expected of the Harbour if it is determined that Hamilton Harbour is experiencing an inevitable regional environmental change not in line with full restoration of BUIs as currently written (e.g. BUI pertaining to *undesirable algae*).

In addition, to be discussed in Part 2 of this report series, is the bioavailability of different forms of phosphorus (that comprise TP) and the sources of these specific forms of phosphorus to the Harbour. This is important as not all forms of phosphorus have equal impacts on environmental systems, and a phosphorus loading from one source may be more biologically significant relative to another despite having equal TP loads. One generality that can be made at this point is that the reductions of TP at the WWTPs is of the right kind of phosphorus (i.e. bioavailable form of phosphorus), meaning the proposed, more intensive review of forms of phosphorus is not expected to change the stance on the necessity of TP loading reductions from the WWTPs. The impact of different forms of phosphorus was examined briefly in Snodgrass and Ng (1985).

Finally, another important point to consider during revision of the TP concentration-loading targets is the expected lag in Harbour response following TP loading reductions due to release of phosphorus from the sediments; this concept is highlighted in a paper written by Chapra and Canale (1991). A semi-empirical model by Chapra and Canale (1991) was developed to characterize both phosphorus and oxygen concentrations during lake recovery and was expressively designed for management applications. The model demonstrated why it is important to go beyond short-term projections (i.e. decade) when evaluating the response of a lake to loading reductions, as phosphorus in the sediments can be released during recovery, making recovery appear slower than expected. After reducing phosphorus loading, the phosphorus concentrations in a lake respond fast at first, then slow due to phosphorus release from sediments - a long-term model is needed to simulate this phosphorus release from sediment. This was found to be particularly important when analyzing scenarios for lakes that have been subjected to serious cultural eutrophication, as Hamilton Harbour has been. The model is unique in that it accounts for changes in process rates when the hypolimnetic DO falls below 1.5 mg/L, i.e. the phosphorus release rate from the sediment increases when dissolved oxygen decreases below 1.5 mg/L.

Such interactions should be kept in mind when evaluating the expected Harbour response to the phosphorus loading reductions; the RAP final target for ambient phosphorus concentrations in the Harbour may not be met for some time despite adequate loading reductions because of the stock of phosphorus being released from the sediments. This point is a good example of how Harbour recovery may not be linear. The Technical Teams during the development of the RAP targets emphasized the need for careful monitoring and some necessary research of the Harbour as incremental changes took place following implementation of remedial measures, in order to gauge future strategy priorities and their likely efficacy (K. Rodgers, personal communication, 2007).

3.7 RAP Technical Team Opinion

As has been described, there is uncertainty around the Harbour's ability to not only attain an ambient TP concentration of 17 µg/L, but also what water clarity and dissolved oxygen conditions will prevail at this TP concentration. The final RAP target of 17 µg/L TP is not a critical Harbour target in itself, but was set to allow for water quality improvements, including the reduction of chlorophyll *a* in the Harbour and concomitant increase in water clarity. The current final water quality target of 17 µg/L will encourage substantial water quality improvements while realizing that results approximating this level can achieve remedial action objectives. The value 17 µg/L is a means to an end, not an end in itself.

Further work is required to quantify the uncertainty in the concentration-loading regression, including, for example, a demonstration that a TP Harbour concentration of 18 µg/L is not a RAP failure if BUIs related to water clarity are being met. Along these lines, if the Harbour TP concentration is above 17 µg/L for one or more of the specified 13 week period, this shouldn't be considered a failure of the RAP in regard to phosphorus targets because of the expected uncertainty in the target of 17 µg/L. The location of where 17 µg/L should be measured (centre station) and the temporal scale (13 of 13 weeks in summer) have consensus in being good metrics to measure success, however, it is the exact value of 17 µg/L that is questionable.

The City of Hamilton is proposing an effluent design objective of 0.15 mg/L for total phosphorus, which equates to 74 kg/d at a flow of 500 ML/d. This is above the RAP final loading targets of 60 kg/d (equates to 0.12 mg/L at 500 ML/d), but significant below current phosphorus loading targets which are approximately three times these values. The design objective of 0.15 mg/L is contingent on efficiency of suspended solids removal, which has been recommended as 3 mg/L TSS as a design criterion (KMK, 2007). The TP loading from the Woodward Ave WWTP is proposed at a level approximately an order of magnitude lower than present. If in the future the RAP revises the final ambient Harbour TP concentration of 17 µg/L to another value, it is significant that the City of Hamilton is using best available technology for their proposed upgrades and reaching effluent TP concentrations (~0.15 µg/L) that were

expected during the early development of the RAP (i.e. TP concentrations on par with that obtained through the installation of sand filters/dual point injection).

The RAP Technical Team supports the TP load reduction outlined in the City of Hamilton master plan. In Part 2 of this report series, a more rigorous analysis is to be done on the derivation of current targets and desirable outcomes (including uncertainty), and any modifications required to meet delisting objectives/address BUIs. The load reductions in the City of Hamilton's proposal are expected to improve conditions in Hamilton Harbour to a level on par with intended RAP goals and therefore their proposal is worthy of support. As outlined in the DO chapter, the proposed effluent TP concentrations are expected to work towards addressing the water clarity BUI, but not necessarily the DO issue. That the established RAP DO targets may be unfeasible and that the Harbour may not meet these targets should not fall on the City of Hamilton. The proposal from the City of Hamilton is accomplishing what the RAP expected of them during the RAP process.

4. Ammonia

4.1 Ammonia Primer

Ammonia (NH_3) is a form of nitrogen and a product of the breakdown of nitrogenous organic matter. In water, ammonia can be found in both the un-ionized (NH_3) and ionized state (NH_4^+), the former being of greater concern as un-ionized ammonia is acutely toxic to aquatic life at elevated concentrations. The provincial water quality objective (PWQO) for un-ionized ammonia is 0.02 mg/L, which is a concentration set to be “protective of all forms of aquatic life and all aspects of the aquatic life cycle during indefinite exposure to the water” (MOE, 1994). While the PWQO is protective of chronic (long-term) toxicity effects, un-ionized ammonia is generally a concern when addressing acute toxicity, or the severe, short-term effects that can be had on the resident fish populations (e.g. fish kills). The un-ionized ammonia concentration at which acute toxicity is of concern, is well above (i.e. approximately 5-10 times) the PWQO. Concentrations of un-ionized ammonia in water bodies are generally compared against the PWQO rather than the acute toxicity limit because the PWQO is the desired upper limit according to provincial policy (MOE, 1994) and because this method is more protective of aquatic life. The percent of total ammonia ($\text{NH}_3 + \text{NH}_4^+$) found in an un-ionized form is dependent on the temperature and pH of the water, thus these factors need to be taken into consideration when determining if un-ionized ammonia present in a total ammonia sample is above or below the PWQO.

Under favourable environmental conditions (presence of oxygen and nitrifying bacteria), ammonia undergoes nitrification (i.e. nitrogen oxidation) to produce nitrite (NO_2^-) and then nitrate (NO_3^-). The sum of $\text{NH}_3/\text{NH}_4^+$, NO_2^- and NO_3^- in water is often referred to as total inorganic nitrogen; these forms of nitrogen are also known as nutrients because algae and other aquatic life require nitrogen compounds for their metabolic processes. Also a commonly discussed nitrogen term is TKN; this stands for total Kjeldahl nitrogen and is the sum of organically bound nitrogen and ammonia. Total nitrogen is the sum of organic nitrogen (TKN) and inorganic nitrogen.

In addition to the issue of toxicity, the presence of ammonia in water is also of concern due to the dissolved oxygen deficit created through nitrification processes. Nitrification consumes 4.6 mg of oxygen for each mg of NH_3 converted to NO_3^- (p.146, Stage 1 Report, 1992), meaning high nitrification rates deplete the water column of dissolved oxygen. A certain minimum level of dissolved oxygen is required by fish and other aquatic biota to sustain life.

4.2 Ammonia in Hamilton Harbour

Hamilton Harbour has a number of different sources of ammonia including municipal and industrial inputs, tributaries and organic matter remineralization. Ammonia concentrations in the Harbour are a function of loads and biological processes as well as flushing losses to Lake

Ontario. Ammonia concentrations are invariably dependent on the time of year as nitrifying bacteria are inactive during cold conditions, i.e. below 6 C (p.146, Stage 1 Report).

Due to the excessive ammonia levels in Hamilton Harbour, in the late 1980s it had been noted that algal uptake was the major factor governing the ammonia regime in the Harbour relative to the nitrification process (Barica, 1991). It should be noted however, that concentrations have decreased in the Harbour since then and processes may have changed. Klapwijk and Snodgrass (1986) indicated that NH_3 loss from the water column is a combination of four mechanisms: nitrification, algal uptake, sediment ammonia demand and washout. Due to the complexities in balancing these losses which act simultaneously, the concentration decline of NH_3 in the Harbour cannot be used as a proxy for the nitrification rate. Klapwijk and Snodgrass (1986) also found a large seasonal variation in nitrification rates in Hamilton Harbour (highest in spring), as well as spatial variation as the nitrification rate was found higher in the hypolimnion (in the June experiment).

Generally, the highest ammonia concentration in the Harbour has traditionally occurred during spring due to build-up of ammonia and reduced exchange with Lake Ontario over the winter. The lowest ammonia concentration is said to occur during summer when ammonia is rapidly oxidized (p.146, Stage 1 Report) and exchange with Lake Ontario is more pronounced (Klapwijk and Snodgrass, 1985). Ammonia concentrations in the late 1980s exceeded (chronic) toxicity standards for approximately half the year (spring and summer) throughout the Harbour (Barica, 1991), and for a short period of time (1-2 weeks) even exceeded (acute) LC_{50} levels (300 $\mu\text{g/L}$ – EPA 1984) (Barica and Vieira, 1988). Not only were N-compounds not uniform temporally, but had significant spatial variation as well - total ammonia and un-ionized ammonia were highest in the Windermere Arm area of the Harbour (Barica and Vieira, 1988).

Because ammonia toxicity and a hypolimnetic dissolved oxygen deficit (eutrophication) were concerns for Hamilton Harbour during the development of the Hamilton Harbour RAP, a reduction in the loadings of total ammonia to the Harbour and the PWQO for ambient concentrations of un-ionized ammonia in the Harbour were goals set to address these water quality concerns. Of focus in this chapter of the report is ammonia toxicity; the consumption of dissolved oxygen by nitrification is more directly discussed in the dissolved oxygen chapter.

4.3 Historical Recounting of Ammonia Goal and Target Decisions

Details and interpretation on the historical development of RAP concentration and loading goals pertaining to ammonia are described in Sections 4.3.1 to 4.3.4.

4.3.1 Discussion Document (1988)

The Discussion Document (1988) initially approached the ammonia issue by stating that “[i]n order to eliminate the toxic concentrations of ammonia and improve oxygen levels, a 50% reduction in ammonia discharges is needed” (p.6). This “blanket statement” calling for a

50% reduction may be an approximation based on the ammonia loadings at the time, since the early development of an ammonia target was explained as follows:

A plot of ammonia loadings to the Harbour versus maximum early spring concentrations in the Harbour is shown in Figure 15. Extrapolation of the best fit straight line through the points in the plot to the 0 mg/L ammonia concentration indicates that during the winter about 3,600 kg/day of ammonia is utilized by algae or is flushed out into Lake Ontario. Therefore, at the present rate of removal, a further 4,200 kg/day reduction in ammonia loading may prevent the build up of ammonia in the Harbour during the winter. (p.132)

Later in the Discussion Document (1988), an ammonia loading reduction from 7500 to 3600 kg/d is prescribed (p.150). Such a loading reduction would result in un-ionized ammonia concentrations no longer exceeding the PWQO and oxygen concentrations in the hypolimnion remaining about 1.4 mg/L. The Discussion Document (1988) is a likely source of some inconsistency as to the required ammonia loading reduction, as later documents reference both 3600 kg/d and 3300 kg/d as targets. Using the ammonia loading of 7500 kg/d and applying a further reduction of 4200 kg/d (as per p.132 of Discussion Document, 1988), the target ammonia loading is 3300 kg/d, not 3600 kg/d as stated necessary on page 132.

Specific objectives from the ammonia sources are also discussed, particularly in regard to loadings from the WWTP. “The ammonia in the municipal STP effluents will probably have to be reduced to 3000 kg/day or about 7.5 mg/L at present sewage flows to prevent build-up of ammonia in the Harbour during the winter and to prevent exceedence of the un-ionized ammonia objective in late spring and summer” (p.144, Discussion Document, 1988). On page 158, more source specific objectives are provided, and a combined loading of 3130 kg/d from the two WWTPs is stated as required to meet the ammonia loading goal of 3600 kg/d; the 3130 kg/d is the sum of a 2510 kg/d target from Woodward Ave WWTP, and a 620 kg/d target from Skyway WWTP. Currently, the Woodward Avenue WWTP has an ammonia loading of ~3000 kg/d (KMK, 2007) demonstrating that the targets developed in the late 1980s will likely need to be revised as the Harbour has not responded as predicted. There is still significant ammonia build-up in the Harbour in spring despite current loadings approaching the original targets; this is likely why a more stringent final target was developed as there was considerable uncertainty in the Harbour response to this original estimate. Uncertainty in required ammonia loadings and the development of a final Harbour objective will be discussed in following sections of this chapter.

4.3.2 Preferred Options Report (1990)

The ammonia issue in the Harbour was addressed in the Preferred Options Report for Hamilton Harbour (1990). Table 1.1 of this report (p.2) listed the conditions current at the time, the impaired uses, the sources of the problem and the current information gaps. Ammonia was pertinent to items #2 – Eutrophication; and #3 – Toxic Contaminants in the Water Column. Under Eutrophication, the source of the problem is stated as: phosphorus and ammonia in

sewage treatment plant (STP) effluents, combined sewer overflows (CSOs), industrial effluents, tributary streams, sediment phosphorus reflux and urban runoff. The relevant information gaps noted were the uncertain response of dissolved oxygen to phosphorus and ammonia reduction, and the uncertain exact loadings from storm events (CSOs and tributary streams). Under Toxic Contaminants in the Water Column, the current conditions at that time were un-ionized ammonia concentrations exceeding PWQOs approximately 50% of the time; this toxicity exceedance rate is consistent with that reported by Barica (1991) for the late 1980s.

The Preferred Options Report (1990) also set out initial management strategies to address the issues identified for the Harbour. Under the section on eutrophication, it is noted that embraced in the term “eutrophication” is the “excessive ammonia loading (7500 kg/d) sufficient to create un-ionized ammonia concentrations above the Provincial Water Quality Objective and low dissolved oxygen concentrations due to the conversion of ammonia to nitrate” (p.28). The eutrophication goals and anticipated conditions in Hamilton Harbour pertinent to ammonia were set out as outlined in Table 8 below.

Table 8: Net ammonia loading targets and environmental conditions as listed in Preferred Options Report (1990), p.30

	1987	Initial Goal (1990)	Final Goal (1995)
Objectives – Ammonia Loading (kg/d)			
Hamilton STP	5300	2270	530
Burlington STP	1150	470	115
Industry	850	400	270
CSOs	200	160	20
Total	7500	3300	935
Conditions: Hamilton Harbour			
Un-ionized Ammonia conc. (mg/L)	0.06	<0.02	<0.02

The targets in the Preferred Options Report (1990) are modified from what was presented in the Discussion Document (1988) as the total ammonia goal became 3300 kg/d from 3600 kg/d, and the objectives for the WWTPs were also reduced to reflect the reduction in target total Harbour ammonia loadings.

It was clear that ammonia loadings were being targeted for resolution of both the toxicity and dissolved oxygen issues; however, in order to simplify addressing two issues that are a result of one parameter (ammonia), ammonia is categorized as an eutrophication issue even though it is also associated with toxicity. As such, this set the stage for the initial management strategy for ammonia:

Recommendation 4.3.8

THAT the loading of ammonia from the sewage treatment plants in Hamilton and Burlington be reduced to 3400 kg/d, by nitrifying the effluent prior to discharge into the

Harbour. This should eliminate ammonia buildup in the Harbour during the winter and reduce concentrations to below the Provincial Objective (File #2). (Preferred Options Report, 1990, p.31).¹⁶

Below recommendation 4.3.8, it is stated that the elimination of the ammonia build-up during the winter is also required to attain a dissolved oxygen concentration of 4 ppm. Thus, the initial loading target of 3300 kg/d total ammonia was set to address both the toxicity and dissolved oxygen issues. This same paragraph in the Preferred Options Report (1990) goes on to state that because of uncertainty concerning the dissolved oxygen levels that can be achieved with reduced ammonia loadings, a water quality model with monitoring is necessary to determine if further loading reductions are necessary. It is assumed that this refers to further loading reductions beyond 3300 kg/d, which is set as the initial ammonia loading target. The reader is referred to “File #2” at the back of the Preferred Options Report (1990), which states that there is substantial disagreement among the experts regarding the improvement in ammonia and oxygen concentrations anticipated from an ammonia loading reduction. File #2 again recommends that modelling be performed to resolve the discrepancy in the predicted response of the Harbour; estimates suggest oxygen improvement of only 0.25 ppm or as much as 4 to 5 ppm (p.5 of Preferred Options Report Appendix).

The final total ammonia loading goal appears to have been developed through a different means. The Preferred Options Report (1990, p.31) states that “[a] previous modelling exercise suggested that ammonia loading would have to be reduced to 935 kg/d to achieve the desired dissolved oxygen concentration”. The loading of 935 kg/d was used as the final ammonia total loading goal (Table 8), and it is assumed that because an updated water quality model with monitoring wasn’t completed by the time the Preferred Options Report (1990) was published (as was deemed necessary below recommendation 4.3.8), that there was reliance on this previous modelling exercise and hence the value 935 kg/d was carried forward in the absence of any updated ammonia loading target.

Thus, the Preferred Options Report (1990) implies that the ammonia initial loading goal was set based on: 1) a reduction required to bring un-ionized ammonia concentrations in the Harbour below the PWQO of 0.02 mg/L; and 2) a reduction required to eliminate ammonia buildup in the Harbour during winter to attain a dissolved oxygen concentration of 4 ppm. The Report (1990) also implies that the ammonia final loading goal stemmed from the significant uncertainty surrounding the ability of the initial ammonia loading goal to actually address the dissolved oxygen issue in the Harbour, and hence a more quantitative and rigorous analysis was desired as a basis for the final ammonia loading goal. Having both the initial and final ammonia loading targets set to accomplish a common goal (address the DO deficit issue) may appear contradictory, but the goals were based on two very different methods aimed to accomplish the same outcome; the more conservative number was used for the final loading target. If there was confidence in the ability of the initial loading target to accomplish no build-up of ammonia in the Harbour over winter (i.e. peak ammonia concentration of 0), then both the toxicity issue and the

¹⁶ Table 4.2 on p.30 of the Preferred Options Report (1990) states ammonia loading should be reduced to 3300 kg/d while p.31 recommendation states 3400 kg/d.

dissolved oxygen consumption issue would have been fully addressed and no further loading reductions (i.e. final goal) would have been necessary; additional water quality modelling would have been redundant.

Because a previous modelling exercise had already shown a much lower total ammonia loading required to meet 4 ppm dissolved oxygen in the Harbour, it was a conservative approach to use 935 kg/d and set it as the final ammonia loading goal. It seems that this value was never intended to be a permanent final loading target, but was meant to act as a place-holder until an updated modelling effort was able to demonstrate either: 1) that the initial ammonia loading goal would address the dissolved oxygen issue in the Harbour (3300 kg/d); or 2) an updated total ammonia loading goal necessary to meet the desired dissolved oxygen regime in the Harbour, be it higher or lower than the results of the previous modelling effort.

Nevertheless, as far as can be determined at this time, the final target of 935 kg/d total ammonia was set following a modelling exercise using an oxygen model, likely the Snodgrass and Ng (1985) biochemical model employing the phytoplankton biomass model (see Dissolved Oxygen chapter for further information). Use of the phytoplankton biomass model by Snodgrass and Ng (1985) determined that an 80% loading reduction in ammonia and soluble reactive phosphorus (SRP) inputs and sediment oxygen demand (SOD = 20% of 1977 levels), as well as a 50% reduction in non-point source phosphorus inputs could result in a minimum hypolimnetic summer DO concentration of ~3.5 mg/L (Snodgrass and Ng, 1985). Thus, modelling efforts by Snodgrass and Ng (1985) demonstrated the difficulty in attaining the desired hypolimnetic dissolved oxygen regime (minimum hypolimnetic DO of 4 mg/L); however, despite the challenges in meeting such (at the time) far-reaching management strategies, they recommended an immediate 80% reduction of ammonia inputs due to feasibility of this one step, its predicted small improvement in hypolimnetic DO, and secondary benefit of reducing potential toxicity to fish. It should be noted that the 80% reduction in ammonia loadings to the Harbour never predicted that the Harbour would meet a minimum hypolimnetic DO of 4 mg/L when this management strategy was undertaken in isolation from other management strategies (reduction in SRP loading, SOD).

The exact determination of 935 kg/d is unclear at this time; however the value is likely 80% of an annual loading value. If an 80% reduction in total Harbour loadings was the method chosen in development of the 935 kg/d final target, then the reduction was based on a loading of 4675 kg/d. The total 1989 ammonia loadings to Hamilton Harbour was estimated as 4458 kg/d (p.151, Stage 1 Report, 1992), and an 80% reduction of this annual loading value is 892 kg/d, which is very close to 935 kg/d. The final ammonia loading target may have been slightly modified from 892 kg/d to reach 935 kg/d following the development of goals apportioned to individual sources (WWTPs, CSOs, industry). The final ammonia loading target for industry (Stelco and Dofasco) of 270 kg/d likely pre-dated/was independent from the development of the total Harbour ammonia loading target of 935 kg/d, and as such was included as is during loading source apportionment. This is implied in the HH RAP *Dialogue* newsletter in 1988 as it stated that “[f]urther controls at Stelco and Dofasco will reduce their discharges of ammonia to 270

kilograms a day by 1989. This program is already underway at a cost to them of \$13 million” (HH RAP, 1988, Dialogue on HH).

Later in the Preferred Options Report (1990) in Table 5.1, action items are listed for the recommendations. In regard to recommendation 4.3.8 (as stated above), ammonia controls at STPs are listed as the implementation measure and the comment to this recommendation is that implementation should only proceed if recommendations 4.3.9 and 4.3.10 were found inadequate (p.56). Recommendations 4.3.9 and 4.3.10 refer to reductions in phosphorus loads from the Hamilton and Burlington STPs in order to address eutrophication issues in the Harbour. Thus, ammonia controls at the STPs were to be considered only after it was determined that phosphorus controls were not enough to address Harbour hypoxia. Also interesting to note is that in File #5 of the Preferred Options Report (1990), it is indicated that ammonia concentration violations are virtually eliminated with diversion of STP discharges to Lake Ontario, although this was not considered a viable option due to strong stakeholder opposition towards lake diversion.

4.3.3 Stage 1 Report (1992)

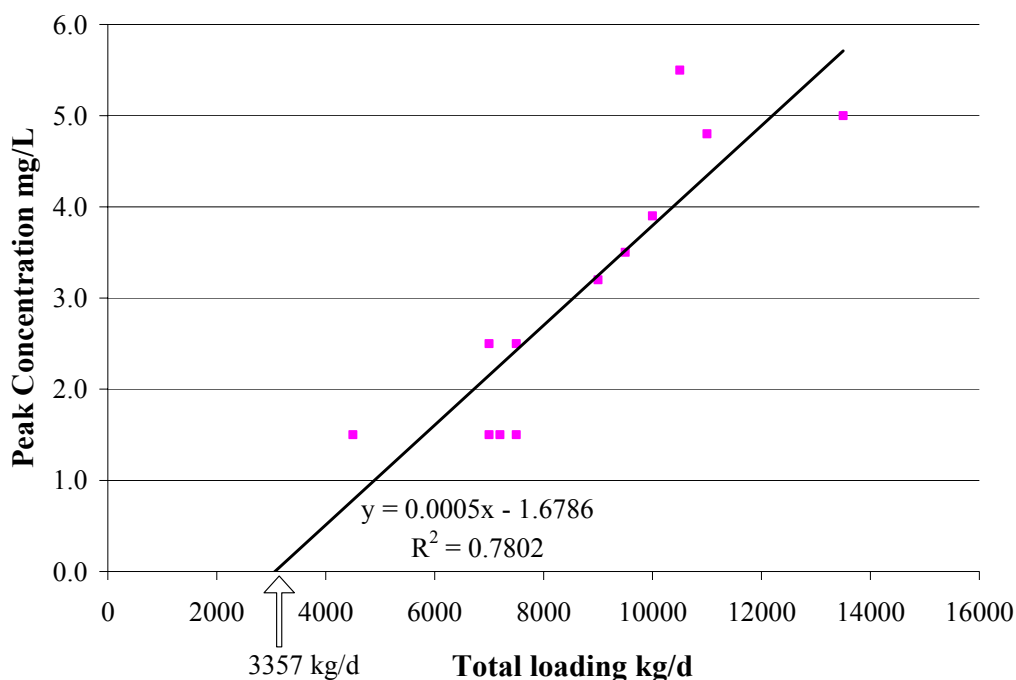
The ammonia issue in the Harbour was again addressed in the Hamilton Harbour Stage 1 Report (1992) with the intention of reducing the loadings to achieve negligible accumulation of ammonia in the winter, as per the intention outlined in the Preferred Options Report (1990). How this initial loading target was determined is explained on p.146 of the Stage 1 Report (1992), and was done by extrapolating the linear regression of annual average ammonia loadings to the Harbour versus the maximum early spring concentrations in the main body of the Harbour¹⁷. The point at which the regression line hits zero total ammonia concentration in the Harbour, corresponds to a Harbour loading of 3300 kg/d, as can be seen on Figure 30 of the Stage 1 Report (1992). This was provided as the initial loading target as it was assumed that at this loading, ammonia might be utilized by algae or flushed out to Lake Ontario, i.e. the Harbour can assimilate ammonia at this loading without contributing to ammonia build-up.

The regression based on the method used in Figure 30 (p.149) was re-created and shown in Figure 2 below. The x-axis intercept does approximate 3300 kg/d using the regression line of ammonia loading and peak concentration data. The loading at the time of the report was 4458 kg/d (1989, figure 32 on p.151 of Stage 1), with 66% of the total from the Hamilton STP, and 13.4% from the Burlington STP.

¹⁷ This statement is somewhat inconsistent with the data presented in Figure 30 (p.149), as Figure 30 indicates “October to March” which is assumed to be referring to the averaging window for total Harbour average ammonia loading values (and possibly also the window used to plot peak ammonia concentrations). This assumption was in part made because the total loading values in Figure 30 are not consistent for all years presented with the total loading values plotted in Figure 29; it is assumed these two figures used different averaging windows to calculate total average Harbour loading, which would explain the different loading values for the same year (e.g. 1988: Figure 29 approximates 5500 kg/d and Figure 30 approximates 7200 kg/d).

Again, this initial loading target of 3300 kg/d is stated to have been “set for improvement of dissolved oxygen demand due to NH_3 ” but also “allow achievement of the [provincial water quality] objective for un-ionized ammonia” (p.147, Stage 1 Report, 1992). The connection between the initial ammonia loading target and dissolved oxygen in the Harbour is reiterated in the Stage 1 Report summary where it is stated that “[o]verall, preliminary loading targets of 3,600 kg/day of ammonia (Figure 30) and 200 kg/day of total phosphorus (Figure 33) for the Harbour are deemed necessary to correct the problem of anoxia, although this will need careful review (Marshall et al., 1988)” (p.170, Stage 1 Report, 1992).

Figure 2: Re-creation of the ammonia peak concentration and average ammonia loading regression as was used to develop the RAP initial ammonia loading target of 3300 kg/d (i.e. Re-creation of Figure 30 in Stage 1 Report, 1992).



As noted in the Discussion Document (1988) section above, there was some inconsistency between use of a total Harbour ammonia loading target of 3600 kg/d and 3300 kg/d. The reference to Marshall et al. (1988) provided in the Stage 1 Report (1992) likely refers to the finding in MMM (1988) that even with great improvements to STP denitrification resulting in lower ambient ammonia Harbour concentrations, dissolved oxygen levels are expected to remain low due to the high oxygen demand created by plankton and sediments (pp.3-6, MMM, 1988). The reference to 3600 kg/d is again repeated in Figure 43 on page 179 of the Stage 1 Report (1992), but presents an inconsistency in the results of this proposed ammonia loading reduction. Figure 43 (p.179, Stage 1 Report, 1992) indicates that a proposed ammonia target of 3600 kg/d should result in an oxygen concentration of 1.5 mg/L, not an oxygen concentration above the PWQO of 4 mg/L as indicated by the target of 3300 kg/d developed

through the concentration-loading regression (Figure 2 above). A Harbour oxygen concentration of 3 mg/L is shown possible on Figure 43 under the scenario of meeting both the ammonia target of 3600 kg/d and the phosphorus target of 290 kg/d. Thus, Figure 43 (p.179) of the Stage 1 Report (1992) indicates that the initial ammonia loading target would not address the DO issue in Hamilton Harbour.

The Stage 1 Report (1992) also alludes to a more stringent ammonia loading target (i.e. final target) as it explains that loading reductions had already improved the ammonia toxicity issue, and that loading targets would have to be even lower to meet the need for improved oxygen conditions (p.170, Stage 1 Report, 1992). Although perhaps not entirely feasible, the initial loading target was set for a dual purpose – to address both the eutrophication and toxicity ammonia issues in the Harbour, by purportedly bringing the total Harbour loading down to a level at which the Harbour can assimilate the loadings and prevent the winter ammonia build-up. The final loading target is not explicitly discussed in the Stage 1 Report (1992).

Another important point mentioned in the Stage 1 Report (1992, p.147) has been commonly referred to as “late season drift”. It is noted that exceedences of the un-ionized ammonia PWQO occurred in late spring and summer when the percent un-ionized ammonia is noted to increase ten-fold due to a rise in temperature and pH; increasing values of both of these variables increase the percent of ammonia in an un-ionized form. While the reason for the temperature increase requires no explanation, the rise of pH from 8 to 8.4 is stated to be caused by the removal of CO₂ from algal photosynthesis. Brief analysis of the NWRI un-ionized ammonia database for samples collected in Hamilton Harbour from 1987 to 2006 shows that the annual peak un-ionized ammonia concentration occurs most frequently in June. Because this time of the year overlaps in terms of potentially experiencing both spring build-up of ammonia and late season drift, it is not clear at this time if late season drift is an important process to consider in addressing peak un-ionized ammonia concentrations.

4.3.4 Stage 2 Report (1992)

The discussion on ammonia loading in the Stage 2 Report (1992) is almost verbatim from the Stage 1 Report (1992); the Stage 2 Report (1992) again indicates that a total loading of 3300 kg/d (or lower) is required to prevent the build-up of ammonia in the Harbour during winter. The Stage 2 Report (1992) does provide greater detail on the sources of ammonia to the Harbour, and proposed remedial actions for the significant ammonia sources. It also indicates that a concentration of about 7.5 mg/L total ammonia from the STPs at the then current day sewage flows would be necessary to prevent build-up of ammonia in the Harbour during winter (p.54, Stage 2 Report, 1992).

The initial and final goals stated in Table A of the Stage 2 Report (1992) are identical to those listed in Table 8 (this report), demonstrating consistency from the Preferred Options Report (1990). Further information is however provided in the Stage 2 Report (1992) on the derivation of the initial and final ammonia loading targets from the WWTPs. It appears that the final target of 115 kg/d for the Skyway WWTP was determined by CH2M Hill Engineering Ltd. (1991) and

was based on a cost-benefit analysis as is mentioned in the Stage 2 Report (1992, Table 18, p.200). Similarly, it would appear that a study by J. Thiel and Associates (1991) set the final NH₃ targets for the Woodward WWTP based on a measure of equity (Stage 2 Report, 1992, p.192). The Stage 2 Report (1992) states that the final WWTP targets were based on having identical concentrations at the two major plant effluents and proportioning the load on the basis of the populations in the late 1980s (p.192). Thus, the final ammonia loading target may have been derived based on results from both the oxygen modelling exercise (to set the total Harbour loading goal) and socio-economic studies of the two WWTPs (to parcel out proportions to the loading point sources). The weighing of different socio-economic and scientific studies on the development of the final targets was a significant challenge to the original RAP Technical Team (K. Rodgers, personal communication, 2007).

4.4 Revisiting and Updating of Historical Methods Used to Determine Initial Ammonia Loading Target

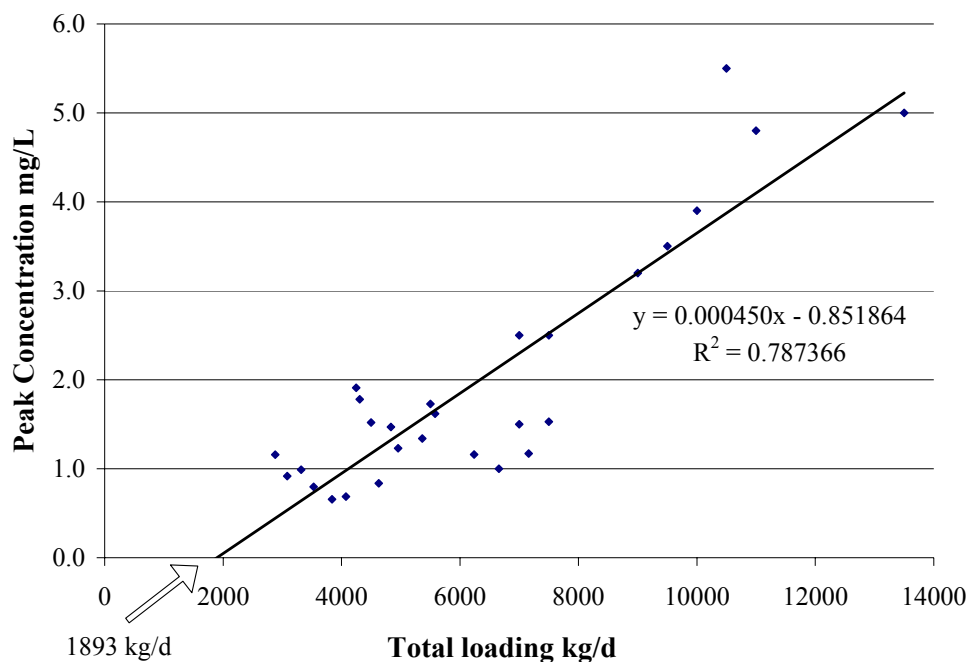
Updating the regression of average annual Harbour loading versus peak concentration for total ammonia (as was used in the Stage 1 Report (1992) and Stage 2 Report (1992)) with recent data, yields an updated loading target (Figure 3). This updated regression estimates that winter accumulation of total ammonia would be negligible at an annual average total Harbour loading of ~1900 kg/d; this value is lower than the initial loading estimate of 3300 kg/d. However, as can be seen from the regression in Figure 2, recent data with lower loading values play a large role in the regression equation and resultant target. Thus the impact of updating of the regression using annual loading averages (as was used in Figure 3 below) instead of October- March loading averages (as was assumed used for development of 3300 kg/d) is assumed negligible due to the large relative differences between historical and more recent data, and also because of agreement for the most part between these two calculated averages as seen for loading values for most years when comparing between Figures 29 and 30 in the Stage 1 Report (1992). Total Harbour loadings have been approaching 1900 kg/d but the peak ammonia concentration remains around 1 mg/L. As is noted in Figure 3 below, there are many uncertainties in this regression (including the choice of averaging windows) and thus the resultant loading target, which should be bracketed with error bars¹⁸. However, all loading estimates in general were subject to variability due to approximations in method and usually sparse data for some sources (K. Rodgers, personal communication, 2007).

As Figure 3 below uses data from a variety of sources/methods, to simplify the regression and to attempt to reduce some uncertainty, a plot of peak ammonia values at centre station versus Woodward WWTP loads was undertaken (Figure 4). As is demonstrated in Figure 4, a linear regression of loads and peak total ammonia concentrations cannot be undertaken, meaning Harbour processes play a large role on Harbour un-ionized ammonia concentrations as the Woodward WWTP is the dominant loading source of ammonia to the Harbour. Although not

¹⁸ Quantification of error such as the inclusion of error bars on regressions will be explored in Part 2 of this report series.

shown here, the same can be said for loads versus annual average total ammonia Harbour concentrations; significant relationships were not found for a number of different regressions plotted. This indicates the noise inherent in the data, and the overwhelming role that the large 1970s loads played into the determination of an initial loading target. This also demonstrates a potential need for modelling (as opposed to regressions) to determine if un-ionized ammonia concentrations will consistently meet the PWQO of 0.02 mg/L, however, any modelling exercise will likely encounter similar issues pertaining to data uncertainty, noise, and the difficulty in explaining complex Harbour processes and there will likely not be an acceptable return-on-investment for modelling efforts spent.

Figure 3: Peak total NH₃ concentration (maximum concentration recorded) as a function of mean annual total Harbour daily loads. Data are for the centre station.



Notes:

*1978-1989 loadings from p.148 of Stage 1 report (estimated from Figure 29, annual average)

*1990-1992 loadings are based on Woodward being 66% of Harbour load

*1993-1995 loadings are based on Woodward and Skyway being 79.4% of Harbour loadings

*1996-2002 loadings from 1996-2002 loadings report (HH RAP, 2004)

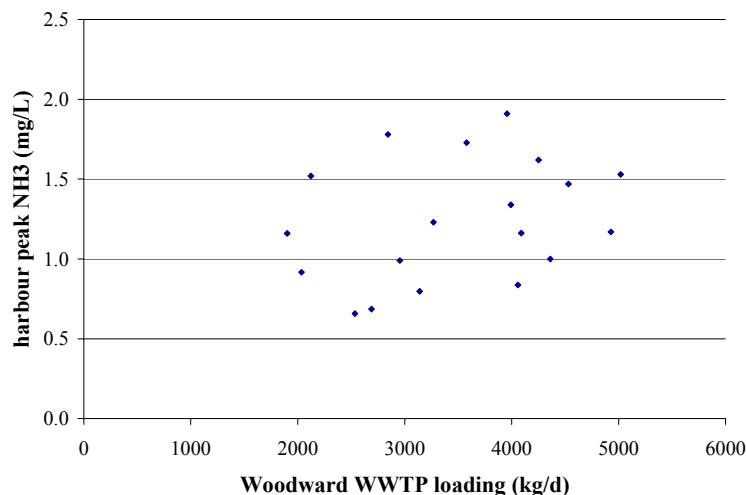
*2003-2006 loadings are based on Woodward being 66% of Harbour load

79.4% of the total Harbour ammonia loading from WWTPs (66% Hamilton, 13.4% Burlington, p.151 of Stage 1 Report).

It should be noted that there is significant error in this regression as the loading numbers were developed through a variety of methods and improved/updated loading values from the WWTPs may be available in the near future.

The extrapolated PWQO for total ammonia is approximately 2 mg/L based on 1% un-ionized ammonia (~17 C, pH = 7.5)

Figure 4: Annual average Woodward Avenue WWTP loads (kg/d) versus peak Harbour ammonia concentration (mg/L) for the years 1987-2006



It was originally expected that as total Harbour loads approached 3300 kg/d (initial loading target), that peak ammonia concentrations would be zero; however, as shown in Figure 2, the Harbour has not responded in this manner as total Harbour loads are currently close to this target yet peak total ammonia concentrations remain around 1 mg/L. Thus, a different approach than that used in the Stage 1 and Stage 2 reports may be needed to determine what loads are necessary to achieve the desired results. The desired results are the delisting objectives related to ammonia toxicity and the dissolved oxygen demand. For the former, 13 of 13 weeks (summer) are to have un-ionized ammonia concentrations below the PWQO of 0.02 mg/L; the delisting objective related to dissolved oxygen is discussed in the dissolved oxygen chapter.

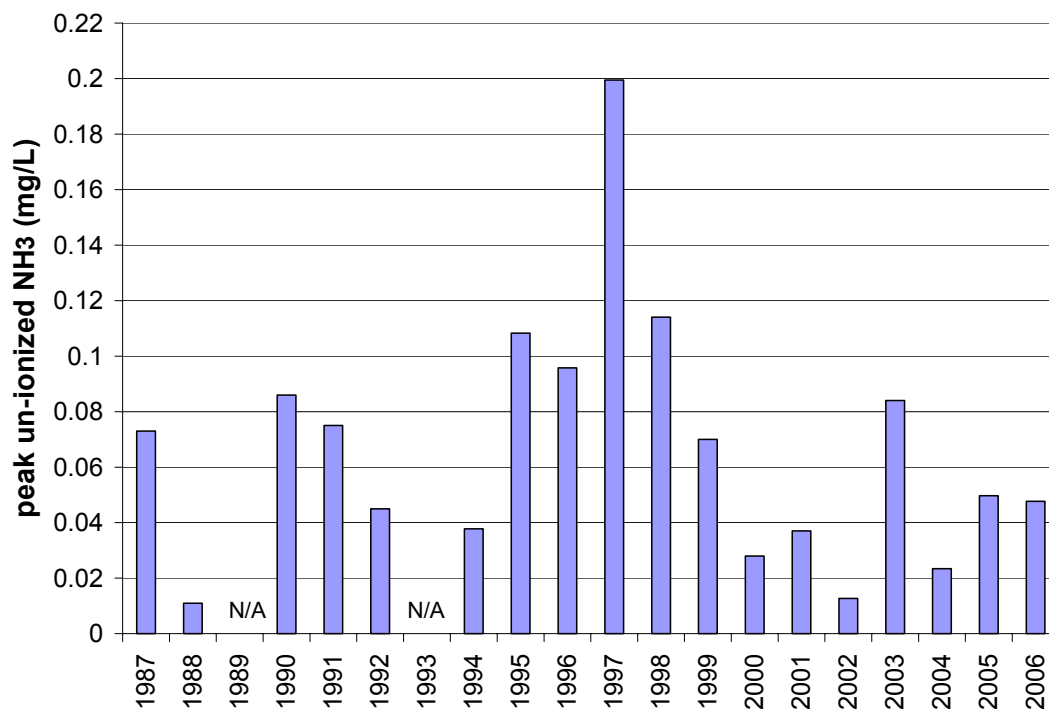
Ammonia concentrations in the Harbour likely do not respond to loads in a linear fashion, but may perhaps be exponential. Thus, at lower loads as per more recent years, loads may decrease with little improvement seen to the Harbour ammonia concentration. Also, the conceptual model used to develop the original regression equation may no longer hold. As ammonia loads have decreased drastically (from ~14,000 kg/d to ~2800 kg/d) while peak ammonia Harbour concentrations have not fallen to the desired concentration for the level of loading reduction seen, it is likely that there are several complicating factors in determining how the Harbour responds to reduced ammonia loading, with temperature and pH being two primary factors. Ammonia concentrations in the Harbour are also likely highly influenced by the level of biological activity as it is used as a nutrient. It was originally postulated in MOE (1985, p.82) that uptake by algae removed significant amounts of ammonia from the water column; this was later confirmed by Barica (1991) in his finding that due to excessive ammonia levels in Hamilton Harbour, algal uptake was the major factor governing the ammonia regime in the Harbour in the late 1980s. It has also been found that the population densities of nitrifying bacteria in the Harbour are extremely variable (MOE, 1985) and therefore this may have an impact on the

variability of ammonia concentrations in the Harbour. Reasons for the difficulty in predicting ammonia concentrations in Hamilton Harbour are many.

4.5 RAP Technical Team Opinion

Despite the difficulty in predicting Harbour response, this chapter aims to determine what ammonia loadings would be required to have peak un-ionized ammonia concentrations less than the PWQO of 0.02 mg/L, i.e. to address potential toxicity in the Harbour due to un-ionized ammonia. The annual peak un-ionized ammonia concentration is shown in Figure 5 below; as demonstrated, the peak un-ionized ammonia concentration still is measured above the PWQO of 0.02 mg/L (except for 1988 and 2002). It should be noted that the un-ionized ammonia data are based on a few instantaneous measurements, and therefore may not be completely representative of more long-term trends in the Harbour. The peaks in Figure 5 were generally measured during the April – August period, with June having the greatest frequency of measured peaks, indicating that this is likely the most difficult time of year to eliminate ammonia toxicity impacts.

Figure 5: Peak un-ionized ammonia concentrations for each year from 1987 – 2006 (no data for 1989, 1993) as measured at Hamilton Harbour centre station. Data are from NWRI database and were collected during ice-free conditions in the Harbour (no or fewer data collected December – March).



A clear relationship between ammonia loads and Harbour concentrations cannot be demonstrated, likely due to the complexities already discussed. As one cannot control overall Harbour processes (i.e. temperature and pH impacts) and/or ammonia from sediment (i.e. historical sources), due diligence regarding potential toxicity is addressed through examination of effluent concentrations rather than loadings. Regarding toxicity concerns, if point source ammonia concentrations meet or come close to the PWQO (chronic guideline), then clearly this will address acute toxicity concerns at the point of discharge. An ammonia loading target requiring an effluent capable of meeting the PWQO from the Woodward Avenue WWTP does not appear to be required from a RAP or regulatory perspective. A complication for RAP Tech Team efforts to confirm a total ammonia loading target, is the natural variability in the Harbour (pH, temperature, etc.) which can result in a range of peak un-ionized ammonia concentrations as a function of one particular annual ammonia loading value. Also to be considered, is how other receiving water bodies in other major urban areas compare – by aiming for no days of un-ionized ammonia concentration above the PWQO, is the Hamilton Harbour RAP goal more stringent than that found in a non-RAP area?

The Woodward Avenue WWTP is proposing a final effluent total ammonia concentration of 2 mg/L (May – November) (p.18, KMK, 2007). Of note is the time period on which the Woodward Avenue WWTP design objective was based, as May to November corresponds to the period of concern to the RAP due to the greatest frequency peaks measured in summer. As seen in Table 9 below for temperature and pH values common in Hamilton Harbour, the un-ionized ammonia concentration corresponding to a total ammonia concentration of 2 mg/L during the criterion period, will meet the PWQO much of the time. This means that the proposed ammonia effluent concentration from Woodward Avenue WWTP will generally meet a more stringent chronic guideline intended to be applied to lakes, not effluent. This point, and the large proposed reduction in ammonia loading to the Harbour, is a significant positive accomplishment.

Table 9: Concentration of un-ionized ammonia (mg/L) at a total ammonia concentration of 2 mg/L (as per MOE, 1994). Shaded cells indicate exceedance of PWQO of 0.02 mg/L.

Temp (C)	pH 7	pH 8
0	0.00166	0.0164
5	0.0026	0.024
10	0.0038	0.036
15	0.0054	0.054
20	0.008	0.076
25	0.0114	0.108
30	0.016	0.15

The RAP Technical Team supports the City of Hamilton’s proposed ammonia concentration as a positive move towards reducing periods of toxicity. However, due to the relationship between ammonia and dissolved oxygen, it was not possible for the RAP

Technical Team to reach a conclusion regarding final ammonia loading targets. The final ammonia concentration target was set lower than the PWQO to improve the complex dissolved oxygen situation in the Harbour; a situation described in the Dissolved Oxygen Chapter. This relationship between ammonia and dissolved oxygen will be explored in greater detail by the RAP Technical Team in Part 2 of this report series.

5. Dissolved Oxygen

5.1 Dissolved Oxygen Primer

Dissolved oxygen (DO) is an important component of water quality as a certain concentration is required to sustain various forms of aquatic life. In particular, guidelines on the DO concentration required for warm and cold-water fisheries have been developed, and are provided in the Ministry of Environment's "Blue Book" (MOE, 1994). As warmer water cannot hold as much dissolved oxygen as colder water, these guidelines are temperature specific; the minimum recommended dissolved oxygen concentration at 25 degrees C (most conservative temperature provided) is 5 mg/L for cold water biota, and 4 mg/L for warm water biota.

Dissolved oxygen is added by photosynthesis and depleted through respiration by plants, animals, and decomposing organic materials. Seasonal dynamics show that oxygen concentration is generally lowest in the (late) summer while mixing events during both fall and spring replenish the water column with atmospheric oxygen. Undersaturation can also occur in winter when ice cover is extensive (Rodgers, 1998). The lake bottom shape (morphometry) will determine how susceptible a lake will be to over extending its DO capacity. For instance, more cone-shaped lakes will naturally have more DO depletion issues relative to lakes that are more bowl-shaped. A cone-shaped lake has a very small volume of bottom waters (hypolimnion) meaning the DO supply in the hypolimnion is used up more quickly relative to a larger hypolimnion in a bowl-shaped lake.

In addition to natural processes, anthropogenic inputs can have a large impact on the depletion of DO in a lake. Oxygen is required for both artificially enhanced biological processes as well as chemical processes. The addition of excess nutrients (phosphorus in particular) leads to eutrophication, increasing the demand for DO since this will cause algae blooms that require oxygen in their eventual decomposition. In addition, ammonia requires oxygen and nitrifying bacteria for nitrification (conversion to nitrite/nitrate). Chemical oxygen demand is also an issue and occurs in the absence of biological processes. An example of this would be oxygen required for breaking down sulphide compounds.

Thus, the DO demand in water bodies is a complicated issue, and although oxygen demand is often primarily attributed to the decomposition of organic material in the hypolimnion, many other factors are involved in the resultant hypolimnetic DO concentration. This can result in an observed volumetric hypolimnetic depletion rate different from the predicted depletion rate due to decomposition of organic matter alone. A paper by Burns (1995) cites nine factors or processes that may explain why the observed depletion rate does not coincide with predicted rates; these factors range from effects of ambient conditions (e.g. DO concentrations, temperature) on reaction rates; unaccounted for oxygen sources (e.g. downward transport of oxygen, effects of inflows, hypolimnetic photosynthesis); choice of averaging window (spatial and temporal variation, including lag in SOD); and lake ecology (algae species present and zooplankton population).

As such, it must remain at the forefront of the RAP discussion that the hypolimnetic DO deficit issue in Hamilton Harbour is highly complex and that any management option chosen to address the issue will have an inherent amount of uncertainty involved for the above noted reasons, and because of unpredictable site-specific responses. Nonetheless, this should not be an impediment in moving forward towards restoration of pertinent beneficial uses, as best professional judgement will be used on how Harbour DO studies should be interpreted in light of the current DO issue and the significance of the current DO delisting objectives.

5.2 Dissolved Oxygen in Hamilton Harbour

Hamilton Harbour has a well documented hypolimnetic dissolved oxygen deficit issue, and although it is generally accepted that much of this is a result of cultural eutrophication (anthropogenic loadings), some degree of eutrophication in the Harbour may have occurred in the past due to the Harbour's more cone-shaped morphometry, water balance and natural nutrient loadings. Reconstruction of past conditions through paleolimnological evidence is beneficial in determining upper limits on what conditions can be expected from the Harbour under less-stressed conditions. Although it is understood that Hamilton Harbour will never reach a "natural" status again under any reasonable timescale, evaluating past conditions relative to present can assist in determining how far remediation efforts should or could proceed.

Yang and Duthie (1993) undertook a stratigraphic analysis of sediment microfossils in a Hamilton Harbour sediment core in order to interpret the impact of human activities on the Harbour since ca. 1660. By primarily using diatoms as indicators of trophic status and the Lake Trophic Status Index (LTSI), Yang and Duthie (1993) concluded that Hamilton Harbour was an oligotrophic water body pre-European colonization but shifted towards mesotrophic in the late 1700s due to deforestation, farming and other early settlement activities. The change in trophic status with European settlement was not unique to Hamilton Harbour as other sediment cores from the region have also demonstrated a similar shift.

Trophic status in Hamilton Harbour generally increased as time progressed except for a brief period of trophic "relaxation" from ca. 1790 attributed to stabilization of the landscape following colonization and/or construction of the Burlington Canal in 1823 which had the effect of increasing water exchange with Lake Ontario. As a note towards the latter, construction of the Burlington Canal has led to mixing levels 30-100% greater relative to the Harbour's natural hydrologic state (Wolfe et al., 2000). Trophic status was again categorized by Yang and Duthie (1993) as mesotrophic in 1853 and trophic status gradually increased and shifted to mesoeutrophic in ~1950 and then quickly to eutrophic in ~1965; the Harbour trophic status has changed little since this time. It should be noted that data became complicated by multiple water quality issues in the twentieth century and some interpretation becomes problematic as Yang and Duthie (1993) indicated that heavy metal contamination in the Harbour modified the succession of Harbour microfossils, more so than eutrophication.

Nonetheless, it appears that the Harbour trophic status has shifted in two stages: 1) to mesotrophic with early European settlement and 2) to eutrophic during intense industrial and municipal growth of the late twentieth century. During remediation to address the Harbour's DO issue, it should be kept in mind that it is likely impossible to restore the Harbour to its "natural" state (pre-European settlement), and therefore the most reasonable best case scenario would be to a state observed during European settlement, that being a mesotrophic state. Part 2 of this report series will examine a target DO regime for Hamilton Harbour that incorporates any DO depletion expected in a mesotrophic system.

The current delisting objectives for Hamilton Harbour in regard to DO are based on currently accepted DO standards, not the historical trophic status of the Harbour or site-specific biological significance. Because Hamilton Harbour is categorized as a warm water fishery (meaning the PWQO of 4 mg/L DO applies), the delisting criteria for the Harbour has an initial goal of >1 mg/L DO and a final goal of >4 mg/L DO (HH RAP, 2003). The Discussion Document (1988) indicates that a minimum hypolimnetic oxygen concentration of 4 mg/L should remain the long term goal for Hamilton Harbour, and a short term goal of 1 mg/L is recommended for a restored benthic invertebrate community; this is because this document also stated that a minimum hypolimnetic dissolved oxygen concentration of 1 mg/L would be satisfactory for most benthic invertebrate populations (p.168). As a secondary benefit, an improvement in hypolimnetic DO was also expected to improve contaminant levels in Hamilton Harbour biota as the presence of oxygen at the sediment-water interface was expected to make the contaminants in the sediment less bioavailable (HH RAP, 1987, p.9). During the latter half of the summer, DO concentrations in the hypolimnion have, and continue to be hypoxic (low in DO) and even anoxic (without DO). Reasons for this are many, including the input of certain anthropogenic compounds that increase dissolved oxygen demand in the Harbour waters.

For such compounds, in this case phosphorus and ammonia, loading targets were developed to serve dual purposes, that being how the loading target would support: 1) the remediation of the hypolimnetic oxygen deficit to meet the RAP ambient DO target; and 2) water clarity (phosphorus) and toxicity (ammonia) related RAP goals; this approach is supported by early work of the RAP as indicated in HH RAP (1987, p.7). Issues described in 2) are discussed in each of their respective chapters (and to some degree, the development of phosphorus/ammonia goals based on meeting the RAP DO target). The Hamilton Harbour beneficial use impairments (BUIs) related to the dissolved oxygen issue are: degraded fish and wildlife populations, degradation of benthos, degradation of phytoplankton and zooplankton, loss of fish and wildlife habitat.

5.3 Historical Recounting of Dissolved Oxygen Goal and Target Decisions

Since the 1970s, models have been used to understand the role of eutrophication and other oxygen demanding processes on the hypolimnetic dissolved oxygen concentration in Hamilton Harbour. Although understanding of the Harbour has increased through the years and

different levels of sophistication have been used to model the Harbour's response to various loading scenarios, the conclusion has remained the same: *It does not seem likely that Hamilton Harbour will achieve no days of DO less than 4 mg/L under the RAP final loading targets.* Models and discussion papers that have provided an analysis that support this conclusion (or provide useful data in understanding the conclusion, i.e. MOE, 1985) are discussed in the following section and include:

- Poulton, 1982
- MOE, 1985 (provides pertinent data)
- Snodgrass and Ng, 1985
- HH RAP, 1987 (provides pertinent data)
- Charlton, 1988 (Draft)
- Barica et al., 1988 (provides pertinent data)
- Marshall Macklin and Monaghan Limited, 1988
- Preferred Options Report, 1990
- McMahan and Snodgrass, 1993
- Kellershohn and Tsanis, 1999
- Charlton, 2001

The only evidence to the contrary found to date is in Vogt (1988). Vogt (1988) indicated that dissolved oxygen concentrations in the hypolimnion could be maintained above 4.8 to 5.8 mg/L once historical bottom sediments are stabilized (and TP inputs are reduced to 240 kg/d with ammonia inputs also reduced), but the model used to provide these dissolved oxygen estimates assumed zero future sediment oxygen demand, which may be an unrealistic assumption (as is the assumption used that effluents to Hamilton Harbour stay in the epilimnion).

The conclusion of likely non-achievability of the current final RAP DO target raises several questions that need to be addressed in order to prepare for delisting; these questions will be considered and acted-upon in Part 2 of this report series.

5.3.1 Poulton (1982)

A two-layer (epilimnion and hypolimnion) horizontally well-mixed DO box model was developed by Poulton (1982) in the late 1970s/early 1980s to better understand the issue of anoxic bottom waters of Hamilton Harbour. Harbour morphometry was not considered; a mean Harbour depth of 13 m was used.

The model considered the following DO sinks:

- a) carbonaceous biochemical oxygen demand (CBOD) in the water column from external CBOD loadings (including tributaries and stormwater) and the internal production of CBOD from photosynthesis;
- b) nitrogenous biochemical oxygen demand (NBOD) in the water column from ammonia loadings from industrial and municipal (including tributaries and stormwater) sources (empirical rate as internal NBOD loadings are neglected due to lack of information on its magnitude);

- c) sulphurous biochemical oxygen demand (SBOD) in the water column with demand rates based on lab measurements of oxygen depletion due to reduced sulphur; and
- d) sediment oxygen demand (SOD) in the hypolimnion only.

The model considered the following DO sources:

- a) photosynthesis (epilimnion only);
- b) re-aeration (epilimnion only); and
- c) mass-exchange with Lake Ontario (inflow assumed to occur to the hypolimnion during summer, while outflow to lake was restricted to the epilimnion).

All industrial and municipal sources and sinks are assumed to discharge into the epilimnion and all rate constants were assumed to be a function of temperature. The model was calibrated with chloride data, and it was found that lake exchange had to be increased 50% to reach observed summer chloride values in the Harbour. Sensitivity analysis found the model to be sensitive to re-aeration. The data used was a composite for several years so full validation was not undertaken (since there was no complete data set for one individual year).

Neglecting the direct modelling of internal NBOD loadings was the primary limitation of the model and may be the cause of spring underestimate of NBOD. Implications of this model deficiency were later discussed in MOE (1985) and indicate that reduction of oxygen demanding nitrogen loads must consider internally produced demand. This is due to the finding that “internally produced nitrogen exceeds the externally loaded nitrogen by a factor of up to 1.6 during the period of maximum algal growth (usually summer)” (MOE, 1985, p.83). At another point, it is mentioned that “ammonification of internally produced organic nitrogen as well as externally loaded organic nitrogen, may exceed 90% of the point source loadings of ammonia during peak accumulation periods in the water column. This implies that organic nitrogen produced within the Harbour (mainly by the phytoplankton) represents a significant source of oxygen demand through ammonification and ultimately nitrification.” (MOE, 1985, p.102). MOE (1985) also indicates that the SOD rate following future reduction of water column BOD and NBOD demands is unknown. This limits the usefulness of the model in predicting the long-term response to certain abatement scenarios (MOE, 1985, p.109).

The model results indicated that 60% of DO demand is in the water column and 40% is due to sediment oxygen demand, but the apportionment of DO demand varies seasonally as 80-90% of total oxygen demand in summer is due to oxygen demand in water column, and 75% in fall. As hypolimnetic DO drops (as it does during summer), the SOD becomes smaller as it varies directly with oxygen concentration, and the bacterial populations in the water column are rapidly increasing (MOE, 1985, p.112).

There is no direct statement regarding the loads required to bring hypolimnetic DO up to 4 mg/L in Poulton (1982); however, results and scenario runs of the Poulton (1982) model are discussed in MOE (1985). The only scenario where mid-summer hypolimnetic oxygen concentrations exceed 4 mg/L is when there is *complete removal of all water column demands* (sediment oxygen demand unaltered); under this scenario, bottom oxygen concentrations by the

end of June are predicted to be 6.4 mg/L and by early September, 4.9 mg/L (p.114 of MOE, 1985).

As oxygen levels are still below saturation under complete removal of all water column DO demands, this is indicative of the high sediment oxygen demand present in the Harbour (internal demand is dictated by primary algal production and its subsequent decomposition, MOE, 1985, p.112). It is noted that sedimentation of organic material, phosphorus and dead algae will replenish the supply of oxygen-demanding material on the bottom, so reductions in SOD will need to come from input reductions of organic material and phosphorus, and a trend towards DO improvement may not be seen immediately (MOE, 1985, p.112).

The model also indicates that greater improvements to DO would be expected with reductions in NBOD loadings relative to reduction in CBOD loadings, and that “[r]eductions in the photosynthesis rate caused by reductions in phosphorus loadings have only a minor effect because of the feedback effect of decreased internal CBOD production accompanying decreased oxygen production” (p.111). It is also indicated that diversion of a) industrial effluent or b) Hamilton WWTP effluent to Lake Ontario would not bring hypolimnetic DO concentration up to the PWQO (early September hypolimnetic DO of 2.0 mg/L and 1.3 mg/L respectively, p.114, MOE, 1985), however, this is implicit in the finding that all water column DO demands must be turned to zero for any hope of achieving the PWQO. In the summary and conclusions provided in MOE (1985), it is thought that the model, although not predicting hypolimnetic DO to desirable levels, is still optimistic in its projections meaning improvements in oxygen levels may be even less than predicted.

5.3.2 MOE (1985)

In addition to outlining results of the Poulton (1982) model, MOE (1985) discusses other data that have been gathered on the hypolimnetic DO issue in Hamilton Harbour. The report is clear in identifying the need to limit primary production as part of any plan to rectify the DO problem in the Harbour, with algal biomass a major contributor to the organic carbon and nitrogen reservoirs which are responsible for much of the oxygen demand in the Harbour. *The MOE (1985) report does however stress the uncertainty in relating reduction in primary productivity to an increase in dissolved oxygen, as it indicates that it was not at the time possible to reliably quantify the relationship between oxygen depletion and the total phosphorus load (p.85). This is likely why there are inconsistent results between the different models discussed throughout this report.*

In an attempt to quantify the components responsible for oxygen demand in the Harbour, several laboratory-based oxygen consumption experiments were carried out. These experiments determined that the contribution of various DO demanding processes to total oxygen demand does not remain consistent throughout the year. The oxygen demand of various components varies seasonally with the following ranges describing the relative role in the total water column oxygen demand:

- Organic carbon decomposition – 10-60%;
- Sulphur oxidation – 20-70%;
- Nitrification – 10-45%.

Also, it was stated that oxidation of methane gas from Harbour sediments accounted for a maximum of 6% of the total water column oxygen demand.

Following the quantification of seasonally dominant oxygen demanding processes, the dominant processes responsible for oxygen demand in the water column at various time of the year were described as follows:

- Late winter through early spring – sulphur oxidation;
- Late spring through early summer – nitrification;
- Late summer through early autumn – nitrification and carbon demand; and
- Late autumn through early winter – carbon demand (p.103).

5.3.3 Snodgrass and Ng (1985)

Snodgrass and Ng (1985) developed a two box oxygen model (epilimnion, hypolimnion) based on nitrification of land-based inputs of ammonia, oxidation of organics formed by autochthonous production and sediment oxygen demand. A phytoplankton biomass model developed by Thomann et al. (1975) was used to calculate the amount of biomass formed *in situ* as well as the amount of ammonia taken up during phytoplankton growth. The paper aimed to determine the relative importance of Kjeldahl nitrogen inputs, autochthonous production, and sediment oxygen demand to hypolimnetic dissolved oxygen. The authors noted that the actual minimum DO in the Harbour hypolimnion may be higher than predicted in the summer due to inputs of oxygen from lake-Harbour exchange.

Results indicated that 25% of the hypolimnetic oxygen demand was due to biomass decay, while the remaining 75% was due equally to nitrification and sediment oxygen demand. This was interpreted such that controls of inputs of land-based carbonaceous materials (allochthonous organics source control) was not recommended as a remediation strategy for addressing the hypolimnetic dissolved oxygen deficit in the Harbour since these sources only explain such a small fraction of the hypolimnetic dissolved oxygen deficit. The most significant improvement to the hypolimnetic dissolved oxygen deficit was expected to occur through a reduction in the rate of ammonia input (to reduce the rate of nitrification), a reduction in the rate of phosphorus input (to reduce the formation of organics), and dredging and/or allowing accumulated organics to decompose or be buried in deep sediment (to reduce sediment oxygen demand).

A number of scenarios were also run by Snodgrass and Ng (1985) to predict DO under various potential water quality management alternatives. These scenarios build on one another in terms of increasing effort and hypolimnetic dissolved oxygen concentration and include the following:

- 1) 80% reduction in ammonia inputs;

- 2) 80% reduction in ammonia inputs and soluble reactive phosphorus (SRP) discharges from WWTPs;
- 3) 80% reduction in ammonia inputs, SRP discharges from WWTPs and SOD (note: as reference, SOD modelled as 20% of 1977 SOD levels);
- 4) 80% reduction in ammonia inputs, SRP discharges from WWTPs and SOD (note: note: as reference, SOD modelled as 20% of 1977 SOD levels), and a 50% reduction in biologically available P from diffuse sources

Output from the models indicated the challenge in obtaining the desired hypolimnetic dissolved oxygen regime as the predicted minimum hypolimnetic DO still did not reach 4 mg/L even under the most stringent scenario (scenario 4 above). The outcome of each of the scenarios is as follows:

- 1) Predicted oxygen improvement is small, but predicted minimum DO is approximately 1 mg/L at the end of July, and the length of time of low DO has decreased and the rate of decline in the springtime has slowed;
- 2) Predicted oxygen improvement over scenario 1; minimum concentration is greater than 1 mg/L;
- 3) Predicted oxygen improvement over scenario 2; minimum concentration is ~2.5 mg/L
- 4) Predicted oxygen improvement over scenario 3; minimum hypolimnetic DO ~3.5 mg/L

The authors concluded that model prediction suggest that “Hamilton Harbour will continue to suffer some degradation with respect to oxygen resources even when extremely good management options are implemented” (Snodgrass and Ng, 1985, p.234). Despite this finding, they still recommended an 80% reduction in ammonia inputs due to the feasibility of this management option, the small improvement in DO expected, and the secondary beneficial impact of a reduction of potential toxicity to fish.

5.3.4 HH RAP (1987)

The HH RAP (1987) document indicated that the main cause of water column oxygen demand in Hamilton Harbour was the oxidation of ammonia (p.24); although this was at a time when ambient ammonia concentrations in the Harbour were very high (Barica and Vieira, 1988). This report indicated ammonia loading reductions possible through various remedial measures and indicated that an 85% reduction in ammonia loadings (from 1985 loadings, i.e. from 7051 kg/d to 1058 kg/d) was possible, which would reduce ambient ammonia concentrations to 0.5 mg/L. The magnitude of this reduction is on par with that recommended by Snodgrass and Ng (1985), indicating consistency in the required ammonia loading reductions.

The HH RAP (1987) report also indicated that sediment oxygen demand is a major cause of oxygen depletion in bottom waters, and that reductions in phosphorus load were recommended to reduce algal growth. Reductions in phosphorous loadings from various sources were recommended, however, the only recommendation that matches a current RAP goal is the reduction to 5 kg/d resulting from the elimination of CSOs (p.25).

5.3.5 Charlton (1988, Draft)

To initiate his work relating lake morphometry and DO concentration, Charlton (1988, draft) cites a relationship developed by Thienemann (1928) that correlates the mean depth of lakes with the hypolimnion oxygen decrease by August. The expected hypolimnetic DO concentration in Hamilton Harbour by the time of destratification according to Thienemann (1928) would be 2.4 mg/L or less; this is without considering pollution (e.g. nitrification):

$$11 \text{ mg/L (max DO)} - 8.6 \text{ mg/L (depletion by Aug for lake with mean depth of 13 m, i.e. HH)} = 2.4 \text{ mg/L}$$

Nitrification would likely deplete any remaining oxygen as it has been estimated that 50% of oxygen consumption in Hamilton Harbour is due to nitrification (as cited in Barica et al., 1988).

Charlton (1988, draft) further described oxygen depletion in the Great Lakes by developing an equation based on empirical data that computes the oxygen depletion rate using depth, temperature and productivity as variables. Curves were developed that described the relationship between ambient chlorophyll *a* concentrations and the oxygen depletion rate. It was found that the equation described conditions for Hamilton Harbour well, despite not including the lake-Harbour exchange and nitrification/inputs from sewage plants.

Similar to what has been described in Hamilton Harbour for the relationship between Secchi transparency and total phosphorus (Charlton, 1997), the relationship between DO and chlorophyll *a* is described such that large reductions in nutrient loads resulting in chlorophyll *a* concentration of 20-60 µg/L would have little beneficial effect on dissolved oxygen; in this range of chlorophyll *a* concentrations, the slope of the curve is very low. At chlorophyll *a* concentrations below 20 µg/L, the concentration of dissolved oxygen in the Harbour would respond strongly to nutrient loading changes which result in lower chlorophyll *a* concentrations. This means that if an observable impact on the dissolved oxygen regime is desired, then returns on investments are not expected to be seen until very large changes to chlorophyll *a* concentrations have been achieved, and chlorophyll *a* concentrations fall below 20 µg/L. In recent years, chlorophyll *a* concentrations during the summer months have ranged widely from approximately 5 µg/L to 25 µg/L, so it cannot be determined at this time if the Harbour has responded according to the relationship developed by Charlton (1988, draft).

Charlton (1988; draft) computed the dissolved oxygen depletion rate required to avoid anoxia and the rate required to leave 4 mg/L in the hypolimnion by mid-September (the time at which re-aeration generally begins again); these rates were 0.09 mg/L/day and 0.06 mg/L/day, respectively (assuming 11 mg/L DO in May). Substituting these rates into the chlorophyll *a*-DO curve, this corresponds to required chlorophyll *a* concentrations of 6 µg/L and 3 µg/L respectively. It was noted that the annual variability for the DO depletion rate is 0.06 mg/L, illustrating the scale of changes required to meet the specified DO criteria. It was also noted that a DO depletion rate of 0.09 mg/L would result in a doubling of days above 4 mg/L. Although a

great success in itself, based on the wording of the goal of ‘no days below 4 mg/L’, this success would not meet the RAP delisting target.

This work can be applied to the RAP final goal for DO to indicate achievability. As the chlorophyll *a* concentration required to achieve the goal of no days of DO <4 mg/L is 3 µg/L, and the final RAP goal for ambient chlorophyll *a* concentrations is 5-10 µg/L, it thus appears that *the final RAP goal for DO will not be achieved for Hamilton Harbour based solely on oxygen consumption due to productivity*. As nitrification is assumed to also play a large role in hypolimnetic dissolved oxygen consumption, and this process is not included in the chlorophyll *a* required concentration of 3 µg/L, the goal of no days of DO <4 mg/L would likely not be achieved even if Harbour chlorophyll *a* concentrations were brought down to 3 µg/L. The final RAP target for chlorophyll *a* Harbour concentrations does not support the DO target of no days less than 4 mg/L DO.

5.3.6 Barica et al. (1988)

Lake Ontario exchange is a unique and important process for understanding the DO regime in Hamilton Harbour. It has been estimated that the oxygen from lake exchange is equivalent to the oxygen supplied to the Harbour as a result of photosynthesis (as cited in Barica et al., 1988). Barica et al. (1988) also cites that Klapwijk and Snodgrass (1986) estimated that 53% of NH₃ is oxidized in Hamilton Harbour and 47% is discharged to Lake Ontario.

5.3.7 Marshall Macklin and Monaghan (1988)

In evaluating the predicted water quality improvements to the Harbour (as measured by DO) as a function of mitigative control options, it was found that under the best case scenario (control of all sources), the hypolimnetic DO was expected to improve by only 3 mg/L (p.3-36) from ~0.5 mg/L. This report also noted that a noticeable improvement to hypolimnetic DO should also result from controlling only Hamilton sources (Woodward Ave WWTP and CSOs) - increase DO by 1 mg/L. Overall, the report concluded that nitrification at the Hamilton WWTP would have a small impact on hypolimnetic DO due to the large effects caused by phosphorus inputs and sediment oxygen consumption. The implementation of sand filters and dual injection was expected to have a large impact to oxygen resources in the Harbour due to the associated reductions in phosphorus loadings.

5.3.8 Preferred Options Report (1990)

File #5 in the Preferred Options Report (1990) indicated that diversion of WWTP discharges to Lake Ontario would result in raising summer hypolimnetic dissolved oxygen concentration to 4 mg/L, but did not provide any information on how this was calculated. Because diversion translates to zero loadings to the Harbour from the WWTPs, this implies that

any loadings greater than zero (i.e. RAP final targets) would be too high to achieve the desired result of 4 mg/L DO in Hamilton Harbour.

5.3.9 Charlton (1993)

A position paper was written by Charlton (1993) in response to a proposal received by the City of Hamilton in 1992 regarding artificial aeration in Hamilton Harbour to address the hypolimnetic dissolved oxygen deficit. Charlton (1993) was not supportive of the aeration proposal due to the perceived lack of benefits to the Harbour. In reaching this conclusion, the author discussed several aspects of the hypolimnetic dissolved oxygen deficit relating to the RAP DO delisting objective of 4 mg/L.

Similar to his 1988 (draft) paper, Charlton made some rough calculations to determine required chlorophyll *a* concentrations and oxygen depletion rates to meet the RAP target of DO never falling below 4 mg/L. Ignoring Lake Ontario intrusions, the chlorophyll *a* concentration would have to be approximately 4 µg/L in Hamilton Harbour to leave 4 mg/L DO by the end of the summer (Figure 4, Charlton, 1993); this is only considering DO depletion due to algal decay. The shape of the chlorophyll *a*-DO relationship curve for Hamilton Harbour explains why no improvement to DO has been seen. The chlorophyll *a* concentration needs to get to the far left of the curve (<10 µg/L chlorophyll *a*) before any noticeable DO improvements are observed; the chlorophyll *a* concentration at which improvements are noticeably realized is lower in Charlton (1993) – 10 µg/L, relative to Charlton (1988, draft) – 20 µg/L. As discussed for Charlton (1988, draft), chlorophyll *a* concentration in Hamilton Harbour in summer presently range from about 5 – 25 µg/L, therefore it is difficult to determine if these relationships hold in practice relative to theory. The oxygen consumption rate for the Harbour (0.15 mg/L/day) and the rate required to keep 4 mg/L DO by the end of the summer (0.05 mg/L/day) are consistent to the measurements examined in more detail in Charlton (1988, draft). Despite the uncertainty in understanding the Harbour DO regime and dynamics, Charlton (1993) expected that as sewage loads were controlled for Hamilton Harbour, oxygen conditions would improve accordingly and hence the redundancy of artificial aeration.

Although the hypolimnetic DO was expected to improve in Hamilton Harbour with a decrease in sewage loads, Charlton (1993) questioned the ability of the Harbour to meet DO specifications in the GLWQA, i.e. RAP final objective of DO to not fall below 4 mg/L. To begin with, Charlton (1993) stated that “[t]here are no data showing...that these specifications were ever met” (p.9) for Hamilton Harbour. Following this, Charlton (1993) demonstrated concern for the ability of the RAP to delist the Harbour with strict adherence to DO objectives; he recommended evaluating the biological significance of the DO regime in the Harbour to determine if any “residual oxygen depletion [following aggressive sewage treatment] would be a tolerable condition not a problem” (p.10). Even if the hypolimnetic DO does not respond in a manner “to meet the possibly unrealistic specifications” (p.10) of never falling below 4 mg/L, Charlton (1993) noted that the improvement in surface water quality in Hamilton Harbour warrants the efforts designed to control eutrophication in the Harbour. Furthering these

statements, Charlton (1993) noted that “[o]xygen depletion remaining after the best sewage treatment should be accepted” (p.18), as few options remain to address the RAP DO goals after implementation of best available technology.

5.3.10 McMahan and Snodgrass (1993)

A model was developed by McMahan and Snodgrass (1993) to re-evaluate RAP water quality loading targets that were developed based on an earlier dissolved oxygen model [Ng and Snodgrass, 1985] that was calibrated using late 1970s and early 1980s data. The McMahan and Snodgrass (1993) updated model was developed to answer the following question:

“What effect will various combinations of nutrient loadings from various sources (eg., WWTPs, tributaries, sewers) have on summer maximum chlorophyll a concentrations in surface waters, and the summer range of hypolimnetic dissolved oxygen concentrations?”

External loading sources to the model included 1984-1992 loadings from the WWTPs (Woodward, Dundas, Skyway), tributaries (Grindstone, Spencer, Red Hill, Ancaster), industry (Stelco and Dofasco; ammonia loadings only), CSOs, and separated storm sewers. External loading parameters modelled included organic nitrogen, ammonia, nitrate, particulate phosphorus, orthophosphate, and nitrifying bacteria. The McMahan and Snodgrass (1993) model also included a phytoplankton and herbivorous/carnivorous zooplankton food web created at Manhattan college by Thomann et al. (1974), a water column nitrification routine and a sediment nitrification/organic decay model. The model included 26 water column and 9 sediment coefficients. Exchange with Lake Ontario waters through the shipping canal was also modelled and calibration of the exchange was based on temperature, TDS, total N and adjusted chloride concentrations; modelled values agreed well with measured data. Two-way exchange was modelled for the epilimnion but for the hypolimnion, only water to the Harbour is modelled. Like the Poulton (1982) model, the epilimnion and hypolimnion were treated as two separate mixed reactors (epilimnion defined as a depth to 6.5 m, hypolimnion defined as below 7.5m), mean morphometry was not considered; data were modelled to represent the centre of the Harbour.

Model output included dissolved oxygen, phytoplankton, carnivorous and herbivorous zooplankton, organic nitrogen, total ammonia, nitrate, organic phosphorus, orthophosphate and nitrifying bacteria, and output values were used to estimate total phosphorus, total nitrogen, Secchi depth (based on phytoplankton concentration) and un-ionized ammonia (based on concentration of total ammonia and pH). The model was calibrated to 10 of the parameters. Due to the high variability in DO concentrations measured in the hypolimnion (much lower near sediments), the hypolimnetic DO concentration was calculated as a straight average of mean hypolimnetic DO concentrations (as opposed to volume-weighted). In the event of annual missing data, another year’s data was used as a surrogate. The model was verified in two steps,

first for 1977 and then for the 1984-1992 period (p.28) for a number of parameters but focused on hypolimnetic DO concentration and water clarity parameters.

Nevertheless, the model had some substantial omissions and uncertainties, including:

- Model was not calibrated to the concentration of the herbivorous and carnivorous zooplankton as no observed data were available; also, phytoplankton growth rates are highly variable;
- Zebra mussels were not included in the model; they are known to have an impact on water clarity;
- Spatial differences in Hamilton Harbour not accounted for (different morphometric and loading conditions can have localized impacts on water quality, i.e. different conditions in Windermere Basin, versus centre station, versus Cootes Paradise);
- Nutrient uptake in Cootes Paradise neglected;
- Short circuiting the loadings from Red Hill Creek, Skyway WWTP and Woodward WWTP to Lake Ontario was neglected; and
- Reduction of sediment oxygen demand (SOD) with decreasing phytoplankton concentration is highly uncertain. The SOD reduction was modelled using the best case loading scenario plus a 75% reduction in the SOD; the actual % reduction in SOD with reduced phytoplankton concentrations was unknown at the time and under investigation by G. Van Arkell at McMaster University (graduate thesis). *Expansion of the model to account for the effect of the decreased organic flux to the sediments should be explored (p.71).*

Four scenarios were modelled by McMahan and Snodgrass (1993):

- (1) implementation of potential remedial actions proposed by the RAP committee:
 - ammonia in WWTP effluent reduced to 7.5 mg/L,
 - total phosphorus WWTP concentration reduced to 0.4 mg/L,
 - total phosphorus loadings from CSOs reduced to 5 kg/d, and
 - total phosphorus loadings from tributaries reduced by 50% ;
- (2) the effect of sand filters at the Woodward and Skyway WWTPs in addition to changes noted in scenario 1
 - reduction of WWTP total phosphorus concentrations to 0.1 mg/L;
- (3) best case scenario
 - reduction of tributary phosphorus loads by 95% and
 - reduction of total phosphorus concentrations in the Woodward and Skyway effluent to 0.05 mg/L; and
- (4) best case scenario with 75% reduction in SOD.

These scenarios can be summarized in that organic N, ammonia, nitrate and total N have the same loadings under all scenarios, but smaller loads of organic P, SRP and total P are used as model inputs when proceeding from scenario 1 to 3.

The first three scenarios examined included some drastic improvement of loadings to the Harbour but still indicated that hypolimnetic DO would likely still have many days with concentration below the RAP goal of 4 mg/L (Table 10); i.e. *the goal of minimum hypolimnetic*

DO concentration of 4 mg/L will likely never be met for Hamilton Harbour. This conclusion was viewed as conservative as the model cannot accurately simulate the change in SOD due to a decrease in the organic flux to the sediments. The desirable impacts (improvements) to the Harbour with changes identified in the first three scenarios were much greater for water quality/clarity parameters relative to changes observed for hypolimnetic DO concentrations. This may be indicative of the relatively large role of other oxygen demanding processes in the Harbour, such as nitrification, when compared to eutrophication processes alone (decay of algal biomass, etc.). Further analysis following development of a nomograph displaying the relationship between TP loadings and the number of days that the hypolimnetic DO is estimated by the model to be below 4, 2 and 1 mg/L, showed that phosphorus loadings to Hamilton Harbour likely cannot be reduced enough to increase the minimum hypolimnetic DO concentration sufficiently to attain a value of 4 mg/L; at a loading of 0 kg/d TP, the average no of days with a DO < 4 mg/L was still 80.

Table 10: Predicted average number of days per year when the hypolimnetic DO concentration falls below specified values

	<4 mg/L DO	<2 mg/L DO	<1 mg/L DO
Calibrated 1984-1992 results (baseline)	137.8	62.8	38.0
Scenario 1	107.2	52.7	23.9
Scenario 2	85.6	43.6	3.1
Scenario 3	83.2	40.1	0.0
Scenario 4	45.8	0.0	0.0

It should also be noted that the maximum chlorophyll *a* concentration in scenario 3 (best case) averaged approximately 7 µg/L, which is within the final RAP goal of 5-10 µg/L and interestingly enough, similar to the concentration of 6 µg/L noted by Charlton (1988, draft) necessary to avoid anoxia in the Harbour. Although large improvements were seen under scenario 4, the minimum hypolimnetic DO concentration was 3 mg/L, which is still less than the RAP goal of 4 mg/L.

5.3.11 Kellershohn and Tsanis (1999)

Kellershohn and Tsanis (1999) modelled eutrophication and water quality in Hamilton Harbour using the Water Quality Analysis Simulation Program (WASP), a three-dimensional water quality model of the United States Environmental Protection Agency (US EPA). WASP was first developed in the early 1980s and was based on the Manhattan College work of Thomann et al. (1975). Kellershohn and Tsanis (1999) calibrated WASP using loadings and conditions for the period May 1991 to May 1992. Four scenarios were run in the model to examine the potential for four remedial measures to improve the Harbour's water quality.

Parameters included in the model were: ammonia, nitrite and nitrate, organic nitrogen, inorganic phosphorus, organic phosphorus, dissolved oxygen, carbonaceous biochemical oxygen

demand, and phytoplankton. Average daily concentration values were modelled, and bathymetry of the Harbour was included. The thermocline was taken to be 5 m deep, and circulation within the Harbour was modelled using another model, IDOR3D, which added complexity to the estimation of Harbour epilimnion and hypolimnion mixing, however sensitivity analysis indicated that using a constant circulation pattern with exchange fluxes balanced in the upper and lower layers separately was acceptable and thus employed for other model simulations. During calibration of DO for the model, modelled hypolimnetic DO was overestimated relative to measured hypolimnetic DO. This was explained such that WASP models average conditions and the measured values are likely extreme values. Re-aeration was considered the largest DO source, and smaller sources included inflow of Lake Ontario water and photosynthesis. Major sinks of oxygen included SOD and nitrification of NH_3 , and smaller sinks included respiration, oxidation and organic phosphorous mineralization.

Four scenarios were modelled by Kellershohn and Tsanis (1999) and compared against the base case which was the calibrated 1991/1992 results:

- (1) natural loadings case (greatest amount of improvement possible);
- (2) CSO improvements (more holding tanks and WWTP capacity; assumed frequency of 1 CSO event/year);
- (3) Industrial elimination (re-routing of all of Stelco and Dofasco discharges to Woodward WWTP with no net increase of loading to Harbour from Woodward WWTP); and
- (4) WWTP improvements (corresponded to the RAPs final targets for TP and TKN).

Results indicated that the DO system experienced the least change of all water quality parameters examined under the scenarios. It is thought that the model demonstrated this lack of response to loading reductions due to the lack of knowledge of how SOD rates would change with modelled loading reductions. This was identified as a knowledge gap to fill in order to more fully understand the response of the Harbour's SOD to reduced loadings over the long-term. These model results in terms of the predicted relative water quality/DO improvements and the main uncertainty in regard to DO response (SOD) are very similar to that found by McMahon and Snodgrass (1993).

Of scenarios 2-4 above, scenario 4 resulted in the greatest water quality improvements, including that for DO (Table 11). While most of the results for the baseline as well as scenario runs have hypolimnetic DO concentrations around 4 mg/L which is the RAP goal, it should be reiterated that the model gives an *average* concentration and the RAP goal is based on *extremes*, i.e. no DO concentration to ever fall below 4 mg/L. As such, it is difficult to interpret the modelling results by Kellershohn and Tsanis (1999) in terms of the absolute RAP goal, except that it appears little relative change from present DO conditions in the hypolimnion.

Table 11: Response of Harbour to loading improvements provided in estimated DO concentrations (mg/L) and % improvements.

	Epilimnion	Hypolimnion
Calibrated 1991-1992 results (baseline)	7.51	3.98
Scenario 1	7.48 (0.38%)	4.52 (-13.58)
Scenario 2	7.51 (0.05%)	3.99 (-0.12)
Scenario 3	7.49 (0.25%)	4.05 (-1.63)
Scenario 4	7.48 (0.40%)	4.25 (-6.80)

Notes: The values presented above are average values, not extreme values as used for RAP goals.

5.3.12 Charlton (2001)

In a paper by Charlton (2001), temporal data on the number of days when hypolimnetic dissolved oxygen falls below 4 mg/L in Hamilton Harbour are presented (Figure 5, Charlton, 2001). These data show that despite the large nutrient load reductions made, there has been little change in the number of days with oxygen less than 4 mg/L from the late 1970s to mid 1990s. The general lack of response of the hypolimnetic DO to substantial loading reductions is empirical evidence of the difficulty that will be seen in attaining the final RAP DO goals.

5.3.13 Interpretive Update - Molot et al (1992)

For investigative purposes, the Molot model which has been used to predict end-of-summer oxygen profiles in stratified lakes (Molot et al., 1992) was used with Hamilton Harbour input data to predict oxygen profiles in the Harbour. Because the Molot model is highly empirical and was calibrated to oligotrophic, Dorset-area lakes, and also doesn't account for DO influxes like Lake exchange (as per Hamilton Harbour), use of the Molot model for predicting dissolved oxygen in Hamilton Harbour is not recommended. Any results provided for discussion should not be viewed with certainty as application of the Molot model in Hamilton Harbour is beyond the scope of that intended by Molot et al. (1992). Also to be noted when considering results are that Molot et al. (1992) indicated that the model is highly sensitive to epilimnetic total phosphorus (TP_{epi}), and that the model doesn't include temperature. Where the Molot model is highly useful as a tool is that the dissolved oxygen profile with depth is based on the morphometry of the water body of interest.

The Molot model was entered into an Excel spreadsheet for calculating dissolved oxygen profile from epilimnetic total phosphorus data. The volume (m^3) and area (m^2) of 1 m depth intervals were calculated in GIS from NOAA 1 m depth contours for Lake Ontario. Input parameters were as follows:

- Area of Hamilton Harbour = 2200 ha (as calculated by GIS for the -1 m depth interval)
- Maximum Fetch = 8 km
- TP_{epi} = as indicated for each scenario

Output results indicated that the entire Hamilton Harbour water column (hypolimnion and epilimnion) was anoxic at 36 µg/L (calculated mean TP_{epi} from 1996-2002 for NWRI centre station data); at 17 µg/L (final RAP concentration target for TP), the epilimnetic DO concentration was approximately 2.5 mg/L and the hypolimnetic DO concentration showed a gradual concentration decrease to anoxic conditions at 23 m depth. These results are not surprising given the model sensitivity to TP_{epi} and the hypoxia demonstrated for Dorset lakes at a TP_{epi} concentration of 15 µg/L. The model generates a poor representation of the observed dynamics in the Harbour and its use in this case is out of context as it was developed for oligotrophic Shield lakes.

5.4 RAP Technical Team Opinion

Based on the review of the literature that evaluated the historical nature of hypolimnetic DO depletion in Hamilton Harbour, the RAP does not find it likely that the goal of Harbour water always above 4 mg/L DO will be met under any reasonable scenario. Thus, the RAP Technical Team will be proceeding, in Part 2 of this report series, with a re-evaluation of DO-related targets to determine what DO goal is biologically meaningful and achievable considering the natural state of the Harbour, its location adjacent to a large urban area and the best cost-effective technology applied by the City of Hamilton at the Woodward Avenue WWTP. The revised DO target is to take into account the biological significance to benthos and fisheries. Temporal DO data series will be added to an existing fish habitat model (Chu et al., 2005) so that water depth, substrate type, and DO can be used together to evaluate the habitat available for both cold and warm water fishes. As a full refinement of a DO target will take some time and the City of Hamilton requires input prior to the release of their Master Planning Report in June 2007, information that is already available must be used in determining how the City of Hamilton's proposed effluent objectives relate to RAP goals.

As it has been determined that there are likely no achievable WWTP effluent objectives that would allow for the Harbour to continuously have a DO concentration above 4 mg/L, the RAP, recognizing the strides and improvements in effluent loads/concentrations proposed by the City of Hamilton and therefore gives support to the City of Hamilton Wastewater Master Plan from a DO perspective. Nitrification effort is not warranted at the WWTPs due to the expected DO conditions persisting. Part 2 of this report series intends to further investigate the primary cause(s) of DO depletion in the Harbour; this investigation will likely include a DO depletion rate laboratory experiment as has been conducted by NWRI in the past.

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