STRATFORD-AVON RIVER
ENVIRONMENTAL MANAGEMENT PROJECT

STATISTICAL MODELLING OF IN-STREAM PHOSPHORUS

Technical Report R-15

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May, 1983

PREFACE

This report is one of a series of technical reports resulting from work undertaken as part of the Stratford-Avon River Environmental Management Project (SAREMP).

This two-year Project was initiated in April 1980, at the request of the City of Stratford. The SAREMP is funded entirely by the Ontario Ministry of the Environment. The purpose of the Project is to provide a comprehensive water quality management strategy for the Avon River Basin. In order to accomplish this considerable investigation, monitoring and analysis have taken place. The outcome of these investigations and field demonstrations will be a documented strategy outlining the program and implementation mechanisms most effective in resolving the water quality problems now facing residents of the basin. The Project is assessing urban, rural and in-stream management mechanisms for improving water quality.

This report results directly from the aforementioned investigations. It is meant to be technical in nature and not a statement of policy or program direction. Observations and conclusions are those of the authors and do not necessarily reflect the attitudes or philosophy of agencies and individuals affiliated with the Project. In certain cases the results presented are interim in nature and should not be taken as definitive until such time as additional support data are collected.

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ABSTRACT

Phosphorus enrichment of the Avon River causes eutrophic conditions to prevail throughout the summer months both above and below the City of Stratford. The reduction of phosphorus inputs to the river system is being considered as one means of controlling this eutrophication. To this end, phosphorus inputs from a variety of urban and rural sources have been estimated, and remedial control measures have been assessed. Phosphorus inputs and in-stream transport are compared, and a black box approach is used to model in-stream processing of phosphorus. With this approach, in-stream concentrations are related to phosphorus inputs in order to predict improvements engendered by input reductions.

Total phosphorus inputs over the May-to-September period were estimated to be 4763 kg. Of this amount, 1052 kg. are exported out of the river system. The remainder may be lost to seasonal or long-term in-stream sinks. The discrepancy may also be caused by a downward bias in the estimation of exports. Fifty percent (50%) of inputs are urban in origin, 44% are from rural agricultural activities and a further 6% are from background sources. The Stratford water pollution control plant is the largest and most concentrated source. Rural overland runoff and urban storm water are the next most significant sources. No single source predominates overall within the basin. Consequently, significant reductions can be made only if several sources are controlled.

With maximum feasible reductions of inputs, in-stream concentrations of phosphorus along the Avon River are predicted to fall 10 to 51%. The greatest reductions are expected below the Stratford Water Pollution Control Plant. Concentrations above Stratford are affected only if rural measures are implemented.

It is not clear that reductions of phosphorus inputs considered in this study will be sufficient to control eutrophic conditions in the Avon River. They will nevertheless lower in-stream concentrations towards the Provincial guideline for phosphorus and will contribute to the control of phosphorus loadings to the Thames River and Lake Erie.

ACKNOWLEDGEMENTS

The advice and assistance of the following people was greatly appreciated: D. Coleman, Dr. T. Dickinson, D. Hayman, Dr. I. Heathcote, Dr. M. Miller, S. Singer and D. Veal. The diligent assistance of V. Sokolyk and other staff of the word processing department was greatly appreciated.

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1. INTRODUCTION

Eutrophication is the most pervasive and complex problem encountered on the Avon River. The manifestations of this are luxuriant growths of attached and rooted aquatic plants in the river. These cause a hazardous amplification of the diurnal cycle of dissolved oxygen concentrations. Eutrophic conditions exist both above and below the City of Stratford (Figure 1). Phosphorus is most likely the limiting nutrient sustaining this plant growth. As such, its control is an important consideration for water quality management on the Avon River. This report presents an analysis of the potential for phosphorus control in the Avon River. Phosphorus inputs are estimated, and input controls are assessed. Phosphorus inputs to the river are then related to in-stream phosphorus concentrations.

The approach to analysis in this report relies on reported or measured statistics and modelling data from other studies since processes in the river basin are too complex to be modelled directly here. This is particulary true of in-stream processes which include physical, chemical and biological activities. Information about these processes is brought to bear in the interpretation of results and the prediction of the impacts of phosphorus controls.

Where they are available, data are presented for a full annual period. Most of the analysis, however, focusses on the May-to-September period inclusive. This is the critical growing season for aquatic plants. Furthermore, the analysis in this report deals primarily with total phosphorus rather than the soluble or bioavailable fractions. Information on the bioavailable fraction, that portion that is readily available to aquatic plants, is provided wherever possible.

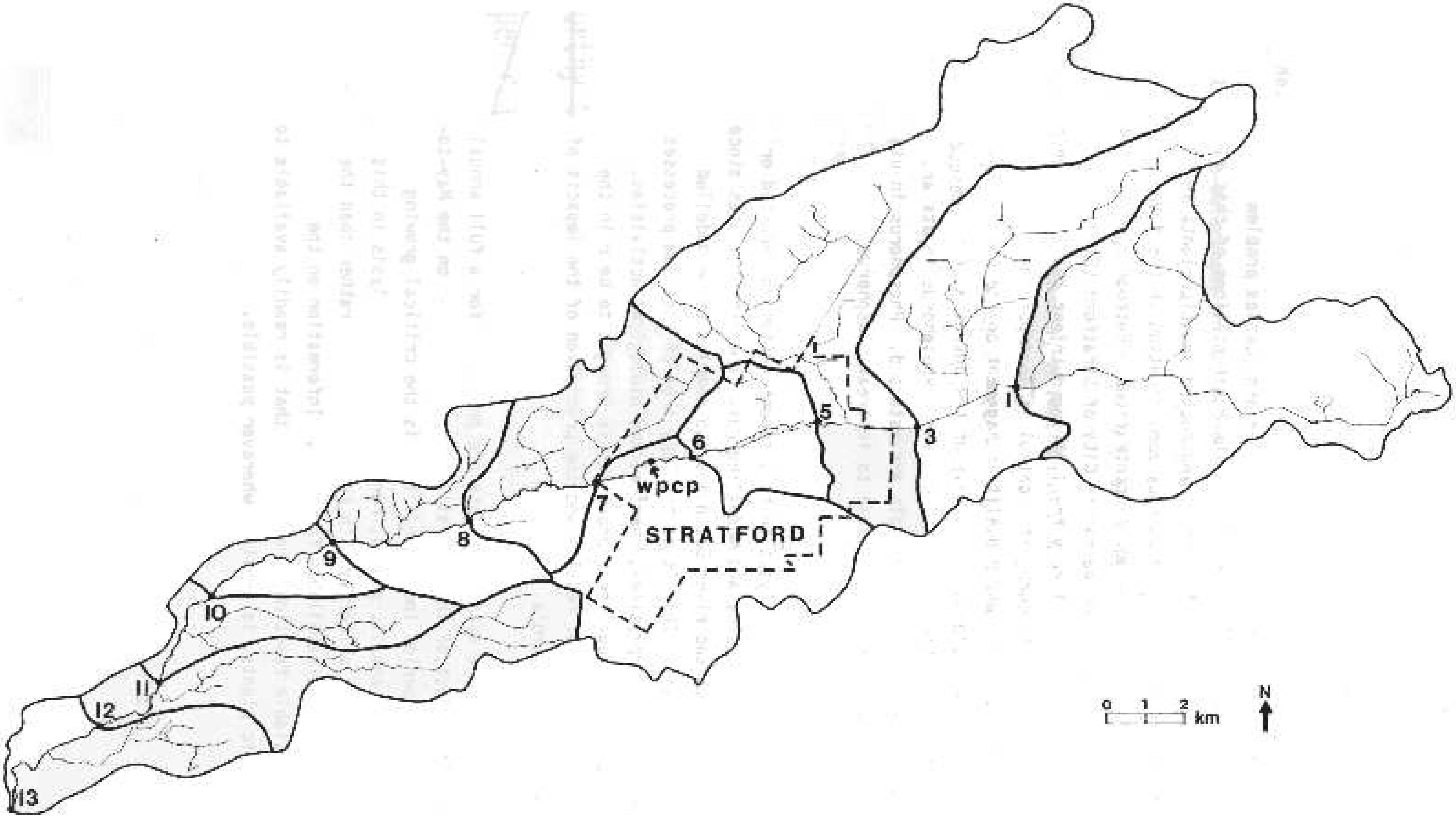

FIGURE 1: Sub-watersheds and Water Quality Monitoring Stations of the Avon River Drainage Basin

2. PHOSPHORUS INPUTS AND CONTROL MEASURES

2.1 Urban Sources

Urban Sources of phosphorus are described in a number of SAREMP Technical Reports.* These are summarized in Table 1. Controls are assumed only for the sewage effluent sources (see SAREMP Final Report). Control of the tertiary effluent load is of particular interest since the proposed control method, dual-stage injection of alum, eliminates 92% of the bioavailable phosphorus in tertiary effluent. This reduction may yield an in-stream biomass impact that is proportionately larger than the impact on in-stream total phosphorus concentrations.

2.2 Rural Sources

2.2.1 Livestock

Loading estimates for the livestock-related sources are listed in Table 2. Loading over the May-to-September period for feedlot and manure pile runoff phosphorus are allocated in proportion to total runoff associated flows over this period. These amount to 17.7% of annual flows occurring during periods of runoff (Appendix 1).

It is assumed that sources identified in Table 2 can be eliminated by measures that will divert contaminated runoff or restrict cattle access. Implementation difficulties may, however, pose a constraint on complete elimination. A 50% reduction is therefore assumed to be feasible.

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* A list of SAREMP technical Reports is provided on the inside of the back cover. In this report, these are referenced by their report number.

TABLE 1: Input Levels And Control Measures For Urban Phosphorus Sources - May To September

Source	Mean Total Phosphorus		Control Measure	Feasible Reduction (kg)	Source Document*
	Concentration (mg/L)	Load (kg)			
Water Pollution Control Plant					
- Sta.6 to Sta.7					
- tertiary effluent	0.35	900	- dual stage alum injection	660	U-4
- bypass effluent	0.4 - 0.5	752	- reduction and storage of storm flows into WPCP	466	U-6
Storm Sewer Wet Weather Flows					
- sta.3 to sta.6	0.5	259	none	-	U-7 and
- sta.6 to sta.7	0.5	44	none	-	background
- sta.7 to sta.10	0.5	124	none	-	files
Storm Sewer Dry Weather Flows					
- sta.3 to sta.6	0.2	230	none	-	U-3 and
- sta.6 to sta.7	0.2	11	none	-	background
- sta.7 to sta.10	0.2	63	none	-	files
Lake Victoria Waterfowl (sta.3 to sta.6)	-	22	none	-	S-1

Note: * See inside back cover for titles of technical reports.

TABLE 2: Phosphorus Inputs From Livestock Activities

SUB-BASIN*	Loadings By Source (kg)				Cattle Access*** Annual
	Feedlot Runoff**		Manure Pile Runoff**		
	May to Sept.	Annual	May to Sept.	Annual	
above 1	83	470	6	33	81
1 to 3	127	717	33	185	38
3 to 6	4	21	2	10	27
6 to 7	0	0	0	0	0
7 to10	39	221	6	31	39
10 to 13	55	309	8	46	19
TOTAL	308	1738	55	305	204

Notes:
* Sub-basins are denoted by upstream and downstream water quality monitoring stations.
** From Hayman (1983)
*** From Demal (1983)

2.2.2 Agricultural Tile Drains

The phosphorus loading associated with agricultural tile drainage flows is estimated using an area loading rate. This rate is influenced by a number of factors including soil type, drainage flow volume, crops and fertilization practices. Estimated loading values spanning a range of conditions are given in Table 3. The mean of these values is 0.22 kg ha^{-1} yr^{-1}, while for lighter more permeable soils the mean value is 0.17 kg ha^{-1} yr^{-1}. This lower value is likely to be more representative of loadings from the predominantly silt loam soils of the Avon basin. Annual loading calculations therefore use this value. In Miller's (1977) research, soluble ortho-phosphorus loadings for light soils ranged from 0.001 to 0.13 kg ha^{-1} yr^{-1} and comprised, on average, 22% of the total phosphorus loadings.

Tile drainage inputs, like feedlot and manure pile inputs, are allocated to the May to September period in proportion to stream flow volumes during runoff episodes that occur during this period (Appendix 1). Thus 17.7% of annual tile drainage phosphorus loadings are assumed to enter the river through this period.

Tile drainage loadings of phosphorus are fixed for this analysis, ie. no control measures are considered for the drainage flows. Loading values are given in Table 4.

2.2.3 Overland Runoff

Estimations of phosphorus loadings from overland runoff are based on the relationship between sediment and particulate phosphorus as applied by Miller *et.al.* (1982):

$$\begin{aligned}\text{Annual Sediment P load} = {} & (\text{total overland sediment load}) \times \\ & (\text{soil P content}) \times (\text{P enrichment ratio})\end{aligned} \tag{1}$$

$$\begin{aligned}\text{Annual Total P load} &= \frac{\text{Sediment P load}}{(1 - \text{dissolved runoff P/total runoff P})} \\ &= \text{Sediment P load} / (1 - 0.24)\end{aligned} \tag{2}$$

The value, 0.24, for the dissolved phosphorus fraction in runoff phosphorus is also based on Miller *et al* (1982). Measurements of the total phosphorus content of basin soils were not available. A mean value for Ontario soils, 0.733 mg g^{-1}, provided by Spires and Miller (1978) is used here. The standard deviation of this value, 0.150 mg g^{-1}, suggests that this parameter is not that variable and that errors introduced by using a provincial mean rather than a basin value are not likely to be large relative to other sources of prediction error inherent in this sort of exercise.

In the same report, Spires and Miller, also develop the following expression to predict the phosphorus enrichment ratio (PER) in field runoff as a function of the clay and sand content of soils and the runoff sediment concentration:

TABLE 3: Reported Phosphorus Yields For Tile Drainage Flows In Mineral Soils

SOURCE	SOILS	FLOW $10^3 m^3$ per ha. yr.	MEAN TOTAL PHOSPHORUS YIELDS kg /ha. yr. (range in brackets)	
Miller (1977)	- clay	3.6	0.48	(0.06-0.64)
	- clay	2.8	0.30	(0.02-0.44)
	- clay	2.5	0.35	(0.21-0.49)
	- sand	1.9	0.24	(0.16-0.30)
	- sandy loam	0.7	0.07	(0.05-0.09)
	- clay	1.8	0.36	(0.10-0.61)
	- sand to sandy and silt loam	1.4	0.14	(0.14-0.15)
	- sand	3.9	0.32	(0.10-0.48)
Bolton *et al* 1970	- clay:			
	no fertilizer	-	0.12	(0.01-0.26)
	fertilized	-	0.19	(0.12-0.29)
Erickson and Ellis,1971	- sandy clay loam	-	0.10	
	- clay loam	-	0.09	
Loehr,1974	- no fertilizer	-	0.11	(0.01-0.23)
	- fertilized	-	0.17	(0.11-0.26)

TABLE 4 : Phosphorus Inputs From Agricultural Tile Drainage Flows

	Phosphorus Loadings By Sub-Basin (kilograms)						
SEASON	above 1	1 to 3	3 to 6	6 to 7	7 to 10	10 to 13	TOTAL
May to Sept.	43	36	35	17	39	49	219
Annual	242	201	199	97	219	278	1236

$$PER = 5.547 - 0.0202\,(SD \times CL) + 0.00128\,(CL^2) + 0.0004(S^2) + 0.455\,(SD^2) - 2.674(SD) \qquad (3)$$

where

CL = % clay in soil (soil particles size less than 0.002 mm)
S = % sand in soil (soil particle size greater than 0.05 mm)
SD = $\log_{10}$ of runoff sediment concentration (mg/L)

Typical particle size fractions for the silt loam soils that predominate in the Avon Basin are (Hoffman and Richards, 1952):

CL = 15%
S = 26%.

Using these values, phosphorus enrichment ratios are given for a range of suspended sediment concentrations in Figure 2.

Sediment loading data is required in order to select a value for the phosphorus enrichment value and then to enable the phosphorus loading calculations. D. Coleman (1983) has estimated a total annual delivered sediment load for the Avon Basin of 6,200 tonnes. Dividing this amount by the total flow volume occurring during periods of runoff (Appendix 1) yields a typical annual runoff sediment concentration of 153 mg L^{-1}. The summer portion of this delivered sediment is estimated to be 9% based on sediment concentrations (Appendix 2) and runoff flow volumes (Appendix 1) at station 10. This fraction is similar to the fraction of annual sediment volumes delivered over the May to September period from 1975 to 1980 on the Ausable River and Canagagigue Creek, 13% and 4% respectively (Water Survey of Canada). Using 9% of annual sediment loads and the summer wet weather runoff flow volume (Appendix 1), the typical summer wet weather sediment concentration is estimated to be 77 mg L^{-1}. These annual and summer sediment concentrations in overland runoff correspond to phosphorus enrichment ratios of 1.8 and 2.1 respectively (from Figure 2). Annual and seasonal phosphorus loadings associated with overland runoff were calculated using these enrichment ratios along with other data provided above and delivered sediment data disaggregated by sub-basin (Table 5).*

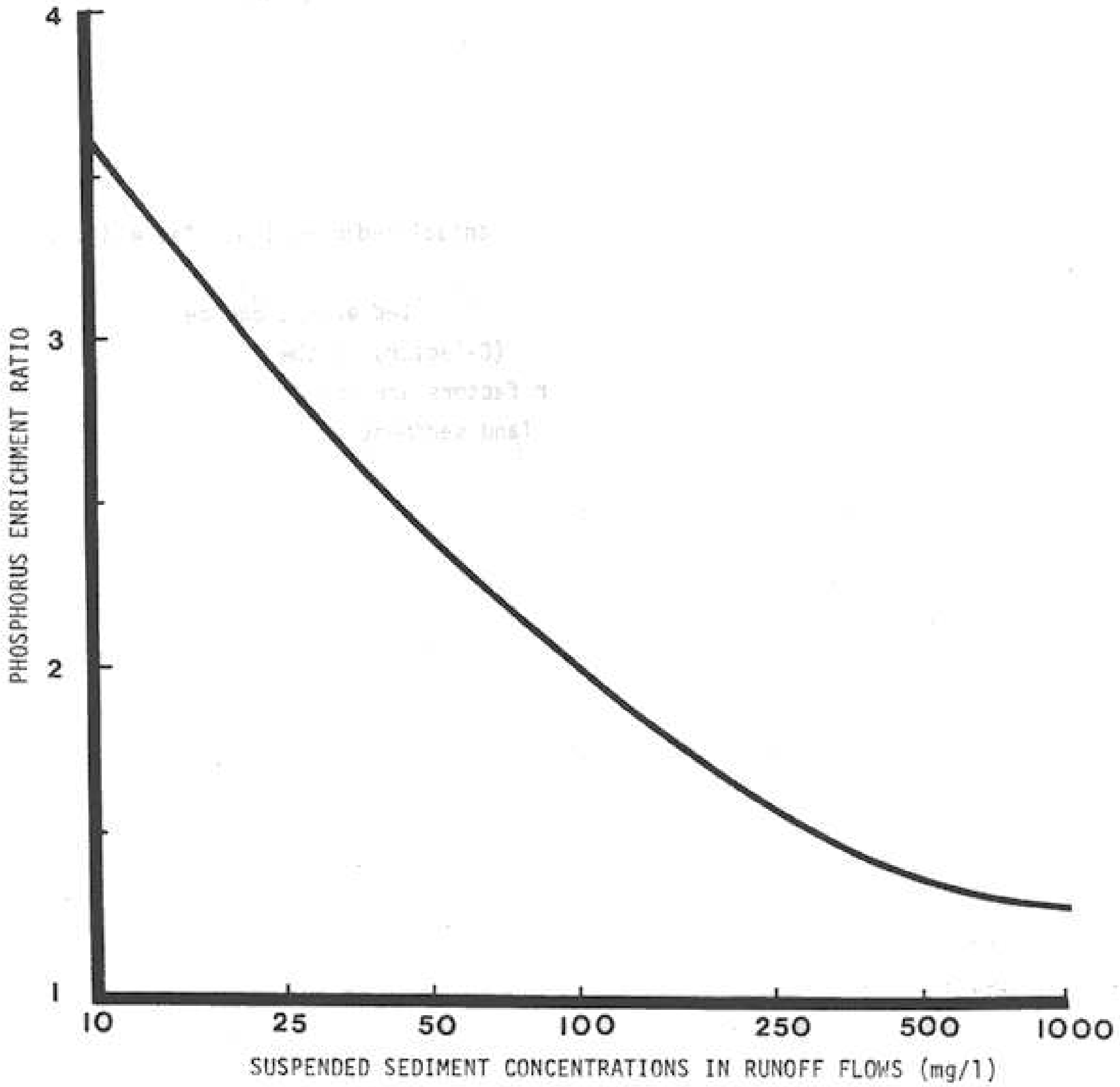

FIGURE 2: Phosphorus Enrichment Ratio Relationship

Crop management measures are considered as means of controlling the phosphorus loading from overland runoff. These include three options:

- fall tillage with a chisel plow
- spring tillage with a moldboard plow
- ridge plant on fields with shallow slopes (2%)
- convert continuous row cropping to a forage based rotation.

These practices are assumed to be applied to cropland currently used for continuous row cropping, a corn rotation system or a mixed system.** Cropland in these categories comprise 12% of the total basin area and account for 86% of the annual sediment load (Table 6).

The impacts of the conservation measures listed above, can be analysed using the crop cover factor (C-factor) of the universal soil loss equation. Assuming other factors are constant and, of necessity, ignoring impacts of overland sediment transport processes, changes in delivered sediment will be proportional to changes in the C-factor. C-factors for the May-to-September period were estimated using the methodology of Wischmeier and Smith (1978). These are presented in Table 6 for the conservation practices noted above and for the existing tillage practice -- fall tillage with a moldboard plow.

Phosphorus loadings do not fall in proportion to sediment loadings when management measures are applied since finer, phosphorus bearing soil particles are more readily transported during episodes of runoff. In effect the phosphorus enrichment ratio may increase with the introduction of conservation measures. Therefore, sediment phosphorus load reductions are assumed to be proportional to sediment load reductions multiplied by a factor of 0.89 (U.S. Army Corps of Engineer, 1982, pg. 136).

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* Delivered sediment data by sub-basin were provided by D. Coleman, personal communication.

** For a description of these systems, see D. Coleman, 1983.

TABLE 5 : Phosphorus Inputs From Overland Runoff Flows

SEASON	Phosphorus Loadings By Sub-Basin (kilograms)						
	above 1	1 to 3	3 to 6	6 to 7	7 to 10	10 to 13	TOTAL
May to Sept	471	148	24	40	277	184	1,144
Annual	4,482	1,411	229	382	2,637	1,750	10,891

TABLE 6: Calculation Of Overland Runoff Phosphorus Loads By Cropping System

	Crop System By Slope Class						
	Continuous Row Crops		Corn Rotation		Mixed System		All Systems
	0-2%	2%+	0-2%	2%+	0-2%	2%+	all
Area(ha) *	2086	244	2364	461	4200	712	16231
Annual Delivered Sediment (tonnes)*	15	1484	12	1736	14	2061	6200
C-Factors, May to Sept.(%):							
- fall moldboard	37		32		17		-
- spring moldboard	34		30		16		-
- fall chisel	28		16		8		-
- ridge plant	24		13		7		-
- rotations ***	17		-		-		-
Total Phosphorus Load(kg):**							
- Annual	80	1700	61	2000	72	2400	10891
- May to Sept.	8	170	6	200	7	230	1144

Notes: * Source: D. Coleman, 1983.

** Phosphorus loadings for each area are determined using the methodology applied for Table 4 results. PER values for the 0-2% slope areas are 5.3 and 6.1 for annual and summer loadings; for the more steeply sloped areas they are 1.2 and 1.3 respectively.

*** Continuous row crop areas converted to mixed system.

The conservation practices are assumed to affect only the sediment associated particulate phosphorus and not the soluble phosphorus fraction (U.S. Army Corps of Engineers, 1982, pg. 139). The soluble fraction, after application of conservation measures, will therefore exceed the 24% value assumed above for the base case loading estimate.

In keeping with the assumptions outlined above, the impact of conservation measures on phosphorus carried by overland runoff is estimated using the expression:

$$\text{Phosphorus Load with a Conservation Measure} = \text{(phosphorus load under existing conditions)} \times (0.24 + 0.76\,(\text{Conservation C-factor/Base-Case C-factor})(0.89)) \quad (4)$$

Phosphorus loadings resulting after the application of conservation measures are provided in Table 7. These are not disaggregated by sub-basin. Sub-basin loadings are assumed to change in proportion to total basin loadings.

Among the conservation measures considered in Table 7, it is evident, given assumptions that are made, that fall tillage with a chisel plow has the greatest impact on phosphorus loadings in overland runoff from May to September. Moreover, most of this impact is provided by treatment of the land area with slopes exceeding 2%*. Accordingly, fall tillage with a chisel plow is the only crop mangement measure that is given further consideration in sections that follow.

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* This result is indicative of the need for targeting of efforts to promote conservation tillage. Factors other than slope may of course be important in selecting target areas; Dickinson, for example, assesses the importance of other hydrologic factors (1981).

TABLE 7: Impact of Conservation Measures on Phosphorus Losses in Overland Runoff From May to September

		Loadings By Crop Area, May To Sept.(kg)				
		Continuous Row Crops	Corn Rotations	Mixed Systems	All Rural Areas *	
Existing (fall Moldboard)		178	206	237	1144	(100%)
Spring Moldboard - slopes:	all	154	181	209	1067	(93%)
	2%+	155	182	209	1069	(93%)
Fall Chisel - slopes:	all	134	119	133	909	(79%)
	2%+	136	122	136	917	(80%)
Ridge Plant - slopes:	0-2%	175	203	234	1135	(99%)
Rotations - slopes:	all	98	206	237	1064	(93%)
	2%+	105	206	237	1071	(94%)

Note: * Control options are applied only to the intensively cropped areas that are treated separately here. Losses from other rural areas do not change.

2.2.4. Streambank Erosion

The final rural source to consider is stream bank erosion. One Canadian study of streambank erosion (Knap *et.al*, 1979) monitored streambank erosion processes and estimated sediment and phosphorus yields for a number of small agricultural basins. Phosphorus yield rates ranged from 0.33 to 10.30 kg km^{-2} yr^{-1} for those basins studied in detail. Among those basins, Canagagigue Creek was nearest to the Avon Basin both geographically and in terms of physiography, drainage intensity, climate and land use.

The yield rate for this basin, 10.16 kg km^{-2} yr^{-1}, is used here to estimate phosphorus loadings from streambank erosion on the Avon. Estimation of the May to September period load is based on the fraction of suspended sediment estimated to be transported past station 10 over this period, 9% (see section 2.2.3 above). Loading estimates are provided in Table 8. A 50% reduction of these loads is assumed to be feasible using structures such as cattle access controls and rip-rapping around tile outlets.

TABLE 8: Phosphorus Inputs From Streambank Erosion

SUB-BASIN	Phosphorus Loading (kg)	
	May to Sept.	Annual
above sta.1	27	304
sta.1to sta.3	22	244
sta.3 to sta.6	34	383
sta.6 to sta.7	13	146
sta.7 to sta.10	22	243
sta.10 to sta.13	16	173
TOTAL	132	1493

2.3 Background inputs

In addition to the sources cited above, there are also natural or background inputs of phosphorus to the stream. These may originate from erosion which will prevail to some degree even without human influence. Phosphorus is of course present in rain water and groundwater so that one would expect to find phosphorus in streams even in the absence of any erosion.

Relatively undisturbed streams to the north of the Avon River, in the Maitland and Saugeen River basins exhibit mean phosphorus concentrations that lie between 0.010 and 0.040 mg/L with the greatest number of these values lying between 0.020 and 0.030 mg/L (MOE, 1981). Ground water from overburden wells in the Avon basin has a mean total phosphorus concentration of 0.027 mg/L (Hydrology and Monitoring Section, MOE, 1982). This value is typical of the undisturbed stream phosphorus concentrations and is used here to represent the impact of natural inputs. Based on flow volumes in Appendix 1, this concentration implies a basin-wide input of 296 kg over the May to September period. This loading is distributed across sub-basins in proportion to area.

2.4 Summary of Inputs

Basin wide inputs of phosphorus are summarized by source in Table 9. The water pollution control plant in the largest source. Overland runoff and storm sewer flows follow. It is notable that total inputs are almost evenly divided between urban and rural sources.

Control measures considered above enable an overall loading reduction of 1637 kg or 34% of inputs during the growing season. Measures at the water pollution control plant are prominent in achieving this degree of control.

Values in Table 9 provide a relatively complete inventory of phosphorus inputs to the Avon River. However, their estimation relies on a number of assumptions that belie the reassurance that may derive from such a detailed quantification. Assumptions that are notable in this regard are:

- that volumes of runoff flow and interflow are proportional to volumes of in-stream flow observed during periods of runoff;
- that various phosphorus loading rates can reliably be applied to a small basin;
- that yield rates for overland runoff can be meaningfully discretized on the basis of slope alone and not other factors such as the hydrologic response of the land base (see Dickinson, 1982).

Phosphorus input estimates must accordingly be interpreted with caution. There is, however, enough information here to suggest that no single source dominates the phosphorus regime in the river and that the feasible level of reduction, 36% through the May - September period, is not as great as one might want.

TABLE 9: Summary Of Phosphorus Inputs To The Avon River

SOURCE	Phosphorus Inputs (kg)			Feasible Reductions May to Sept.
	May to Sept.		Annual* (Rural only)	
Water Pollution Control				
Plant - tertiary effluent	900		-	660
- bypass effluent	752		-	466
- Sub-Total	1652	(35%)	-	1126
Storm Sewers				
- wet weather	427		-	0
- dry weather	304		-	0
- Sub-Total	731	(15%)	-	0
Lake Victoria Waterfront	22	(0.5%)	-	0
Livestock - feedlot runoff	308		1738	154
- manure pile runoff	55		305	28
- cattle access	204		204+	102
- Sub-Total	7	(12%)	7247+	284
Subsurface Drains	219	(5%)	1237	0
Overland Runoff	1144	(24%)	10800	235
Streambank Erosion	132	(3%)	1493	66
Background	296	(6%)		0
TOTAL	4763		15777+	1711

Note: * Estimates of annual urban loads are not available.

3. IN-STREAM TRANSPORT OF PHOSPHORUS

Exports of phosphorus from each sub-basin for the May to September period were calculated using flow volumes and concentration data found in the Appendices. These estimates are reported in Table 10 along with flow weighted mean concentrations and the sum of estimated local inputs to the stream from sources in each sub-basin.

In Table 10, the input and export data are not directly comparable. Each export figure represents the total amount of phosphorus that passes out of a sub-basin over the modelled period. Thus, total exports from the Avon Basin are 1052 kg and not the sum of the individual export values. The exported phosphorus from an upstream catchment is , in effect, an input to the adjacent downstream catchment. The local inputs, on the other hand, represent primary loadings to the river system. Total inputs to the entire Avon Basin are therefore the sum of each of the local sub-basin inputs.

It follows from results in Table 10 that total inputs, summing to 4,763 kg, are not all exported from the Avon Basin at least within the period considered here, since phosphorus exports at station 13 which leave the basin amount to only 1,052 kg. This finding is not unexpected. A failure to adequately sample high flows which carry the bulk of suspended sediments will cause a downward bias in the estimate of phosphorus exports. Apart from this type of measurement error, discrepancies between seasonal inputs and exports are expected because of the loss of phosphorus to seasonal and long term sinks in the stream. Phosphorus may be lost to bed sediments by settling of suspended sediments or by direct absorption (Harms, *et al* 1978). These losses may subsequently be scoured and transported downstream by heavy runoff flows. Bioaccumulation in algae represents a seasonal sink due to the luxuriant growth of nuisance algae occurring through the summer (Thornley, 1982). Hill (1981) found a 90% in-stream loss of dissolved phosphorus during summer low flow periods and a 29% loss over an annual period.

TABLE 10: Comparison Of Phosphorus Inputs And Exports By Sub-Basin

SUB-BASIN	Total Phosphorus, May to September		
	Sum Of Local Inputs (kg)	Exports (kg)	Flow Weighted Mean Concentration* (mg/L)
above sta.1	754	93	0.059
sta. 1 to sta.3	438	180	0.063
sta. 3 to sta.6	719	523	0.089
sta. 6 to sta.7	1849	1254	0.146
sta. 7 to sta.10	650	1154	0.115
sta.10 to sta.13	355	1052	0.096

Note: * Concentrations measured at the downstream end of inputs reach.

A mass-balance model of the interaction between phosphorus inputs to a river reach, stream sinks and phosphorus exports is depicted in Figure 3. For reach "i", the equations describing this mass balance are:

$IL_i + IM_i = E_i + L_i$, and

$E_i = IM_{i+1}$

where:

IL_i = local phosphorus inputs,

IM_i = phosphorus inputs imported from upstream reaches,

E_i = phosphorus exported to the downstream reach,

L_i = phosphorus lost to in-stream sinks.

Using this model, the data in Table 10 is interpreted in Figure 4 to more clearly define the relationships between inputs, and exports of phosphorus. The unaccounted for or lost portion of phosphorus inputs to these reaches varies from 87% in the headwater area to 29% in the last reach.

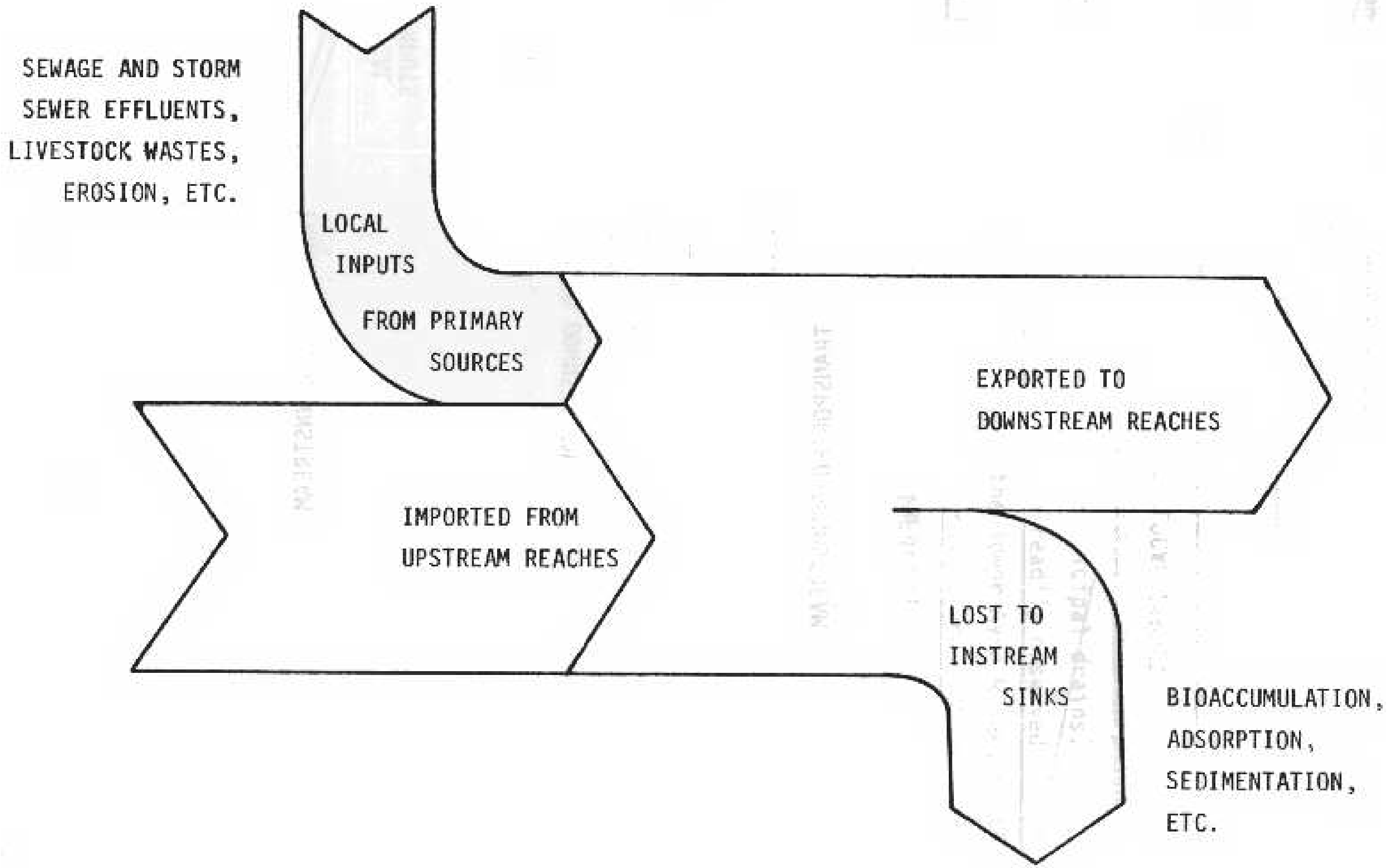

FIGURE 3: In-stream Processing Of Phosphorus

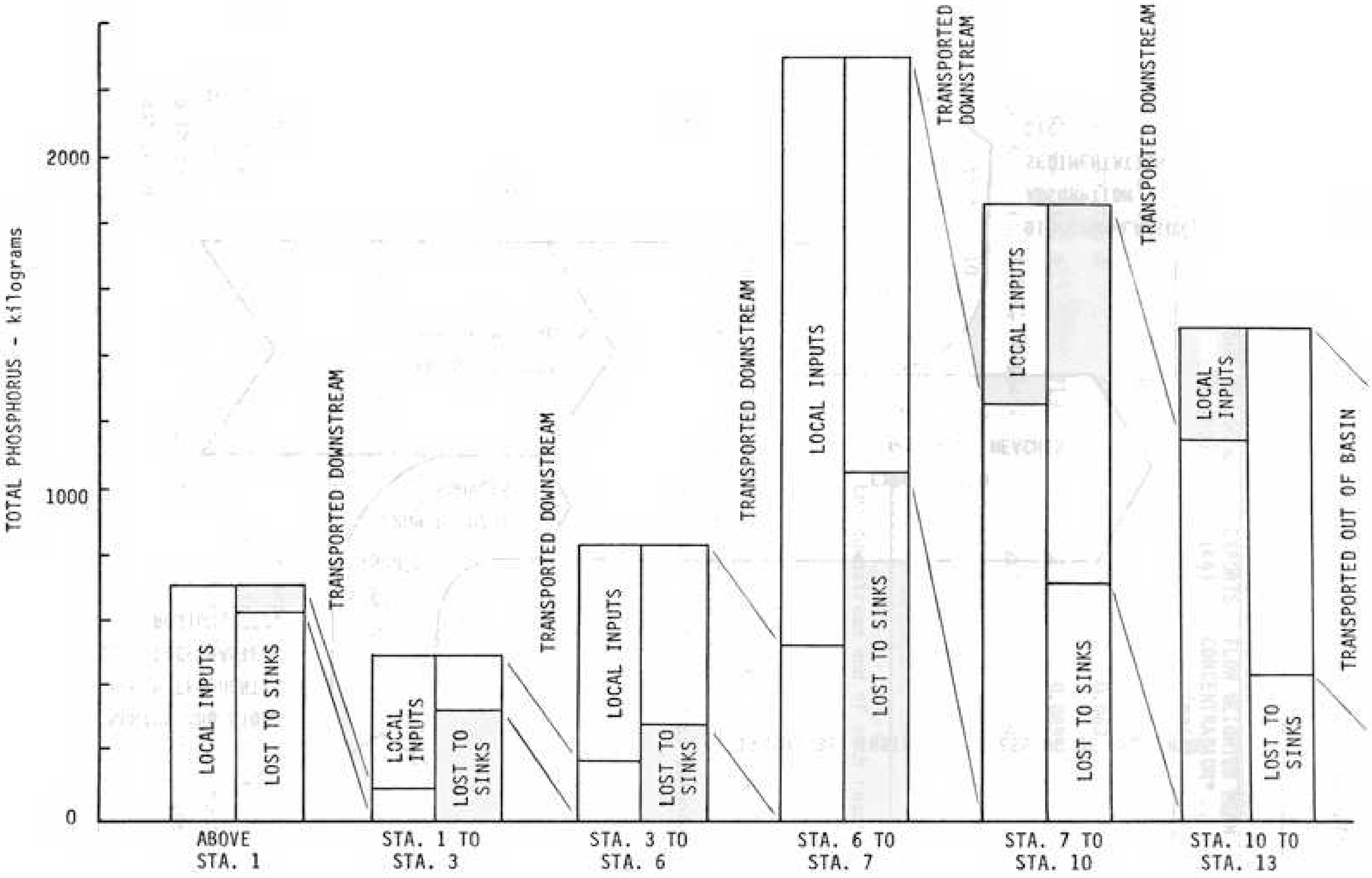

FIGURE 4: Inputs And Exports Of Phosphorus By Reach From May To September

It does not appear that bioaccumulation can account for a significant portion of the lost phosphorus in the stream below Stratford (station 7 to station 13). Over this stretch, total aquatic biomass growth was estimated to be 49,500 kg in 1981 (Thornley, 1982). Sampled plant tissue had a mean observed phosphorus content by weight of 0.39%. This implies a total uptake of only 193 kg compared to a total estimated phosphorus loss over this stretch of river of over 2000 kg. Measurement errors and losses to bed sediments therefore are more likely explanations of estimated losses.

It is noteworthy that the highest proportionate losses of phosphorus occur in upper reaches where channels are municipal drains.

Sediment accumulation in these drains is a readily observed phenomenon. The streambed material of the lower Avon River, on the other hand, consists primarily of sands, gravels and cobbles with little evidence of significant sediment accumulation.

4. ESTIMATED REDUCTIONS IN IN-STREAM PHOSPHORUS CONCENTRATIONS

Phosphorus inputs to the Avon River are described in section 2 while stream processing of these inputs is assessed in a cursory manner in section 3 using a "black box" model of a river reach. In this section this model is applied to predict the impact of loading reductions on in-stream phosphorus concentrations. To do this, the following assumptions are made:

a. flow weighted concentrations of total phosphorus at the end of a reach are proportional to exports of total phosphorus from that reach,

b. the percentage of total phosphorus inputs to a reach that are lost to stream sinks remains constant as total inputs change.

The first assumption above is relatively straight forward. The second is a "black box" assumption that begs many questions regarding the fate of phosphorus once it enters the stream system. Together, these two assumptions tie changes in in-stream concentrations of phosphorus to all upstream inputs, giving greater weight to those inputs which are approximate.

More formally, from assumption (a) the total phosphorus concentration at the end of reach "i" changes from C_i to C'_i after phosphorus exports from that reach change from E_i to E'_i in a proportional manner:

$$C_i / C'_i = Ei / E'_i \qquad (5).$$

As a result of assumption (b), we can define the proportion of exported phosphorus for reach "i" as:

$$e_i = E_i / (IL_1 + IM_i) = E'_i / (IL'_i + IM'_i) \qquad (6).$$

Exports of phosphorus from reach "i" after remedial efforts are implemented can then be defined as:

$$\begin{aligned} E'_i &= e_i\,(IM'_i + IL'_i) \\ &= e_i\,(E'_i + IL'_i) \\ &= e_i\,\left(e_{i-1}\,(IM'_{i-1} + IL'_{i-1}) + IL'_i\right) \\ &= e_i\ IL'_i + e_i\,e_{i-1}\,IL'_{i-1} + \ldots + (e_i\,e_{i-1}\,\ldots\ldots e_i)\,IL'_i \qquad (7) \end{aligned}$$

Local phosphorus inputs under existing and a variety of alternative remedial control options are given in Table 11. Using these values and the model described by Equations 5, 6, and 7, in-stream phosphorus concentrations for various control options were estimated (Table 12).

A comparison of relative magnitudes in Table 12 reveals that controlmeasures at the water pollution control plant provide the greatest impact on in-stream phosphorus concentrations but of course only affect the river below Stratford. Among the rural measures, conservation tillage shows the greatest promise though cattle access controls are not far behind.

A limiting concentration of in-stream phosphorus for the algae, *Cladophora glomerata*, was estimated to be 0.06 mg/L (Painter *et al*, 1976). Only two stations, 1 and 3, are at this level under existing conditions. Rural remedial measures may reduce phosphorus concentrations to below 0.05 mg/L at these stations and should therefore have some impact on nuisance algae growths. Within and below Stratford, however, existing concentrations exceed the limiting level and are brought down to that level only at station 13 under option 10 involving all remedial actions. It is not clear that this reduction would ameliorate the eutrophic conditions observed below the city. These observations are tentative in nature considering the approximate nature of the analysis in this report. Confirmation of these results must await further research and monitoring.

TABLE 11: Estimated Changes In Phosphorus Inputs

	SUB-BASIN					
	above 1	1 to 3	3 to 6	6 to 7	7 to 10	10 to 13
CONTROL MEASURE [a]:						
NONE	754	438	719	1849	650	355
1. WPCP P-Removal	754	438	719	1189	650	355
2. WPCP Bypass Control	754	438	719	1383	650	355
3. WPCP P-Removal and Bypass Control	754	438	719	723	650	355
4. Manure Management[b]	709	358	716	1849	628	324
5. Cattle Access Control	714	419	706	1849	631	346
6. Conservation Tillage [c]	660	408	714	1841	595	318
7. Streambank Erosion Control	742	428	704	1843	641	348
8. Manure Management And Cattle Access Control	668	339	703	1849	608	314
9. All Feasible Rural Measures [d]	562	299	682	1835	543	270
10. All Feasible Measures [e]	562	299	682	709	543	270

NOTES:
- a. All measures are as defined in section 2.
- b. Control of runoff from barnyards and manure piles
- c. Fall chisel plow tillage of intensively cropped areas with slopes exceeding 2%.
- d. Options 4, 5, 6 and 7 combined.
- e. Options 3 and 9 combined.

TABLE 12: Estimated Changes In In-stream Phosphorus Concentrations

	Water Quality Station					
	1	3	6	7	10	13
CONTROL MEASURE[a]:						
NONE	.059	.063	.089	.146	.115	.096
1. WPCP P-Removal	.059	.063	.089	.105	.094	.083
2. WPCP ByPass Control	.059	.063	.089	.117	.100	.086
3. WPCP P-Removal and Bypass Control	.059	.063	.089	.077	.079	.073
4. Manure Management[b]	.055	.053	.086	.145	.113	.093
5. Cattle Access Control	.056	.060	.087	.145	.113	.094
6. Conservation Tillage[c]	.052	.058	.087	.145	.111	.091
7. Streambank Erosion Control	.058	.062	.087	.145	.114	.095
8. Manure Management and Cattle Access Control	.052	.050	.084	.144	.111	.091
9. All Feasible Rural Measures[d]	.044	.044	.080	.142	.106	.085
10. All Feasible Measures[e]	.044	.044	.080	.072	.070	.062

NOTES:
a. All measures are as defined in section 2.
b. Control of runoff from barnyards and manure piles
c. Fall chisel plow tillage of intensively cropped areas with slopes exceeding 2%.
d. Options 4, 5, 6 and 7 combined.
e. Options 3 and 9 combined.

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APPENDIX 1 - SEASONAL FLOW VOLUMES

Flow records at station 10 (the Federal gauging station GD018) for 1980 and 1981 and for the historical period of record, 1965 to 1981, were investigated to determine whether flows for the 1980-81 study period were typical. Mean monthly flows, plotted in figure Al, reveal that the 1980 flows follow the long term trend very closely while the 1981 data has a seasonal distribution that is advanced somewhat. On the other hand, the mean discharge for the long record, 1.77 $m^3 sec^{-1}$, is closer to that of 1981, 1.74 $m^3 sec^{-1}$, than of 1980, 1.59 $m^3 sec^{-1}$. The similarity of the seasonal flow pattern to the long term record plus the fact that runoff water quality data for storm sewers and rural overhead are modelled using 1980 conditions argues in favour of an analysis of seasonal discharge based on 1980 data.

Based on a review of daily mean flows, hourly flows and rainfall data, the 1980 daily mean flow record was divided into wet weather and dry weather periods. These flows were further divided into seasonal periods:

- the summer growing season - May to September
- the fall and Winter period - October to March (excluding snowmelt flows occurring after December)
- the spring runoff period - February to April plus earlier snowmelt runoff flows.

Results of this analysis are as follows:

Period	Summer		Fall/Winter		Spring Runoff
	dry	wet	dry	wet	
Flow Volume (10^3m^3)	2,873	7,202	5,287	8,429	24,975
Mean Flow (m^3sec^{-1})	0.350	1.437	.546	2.168	5.162
Duration (days)	95	58	112	45	56

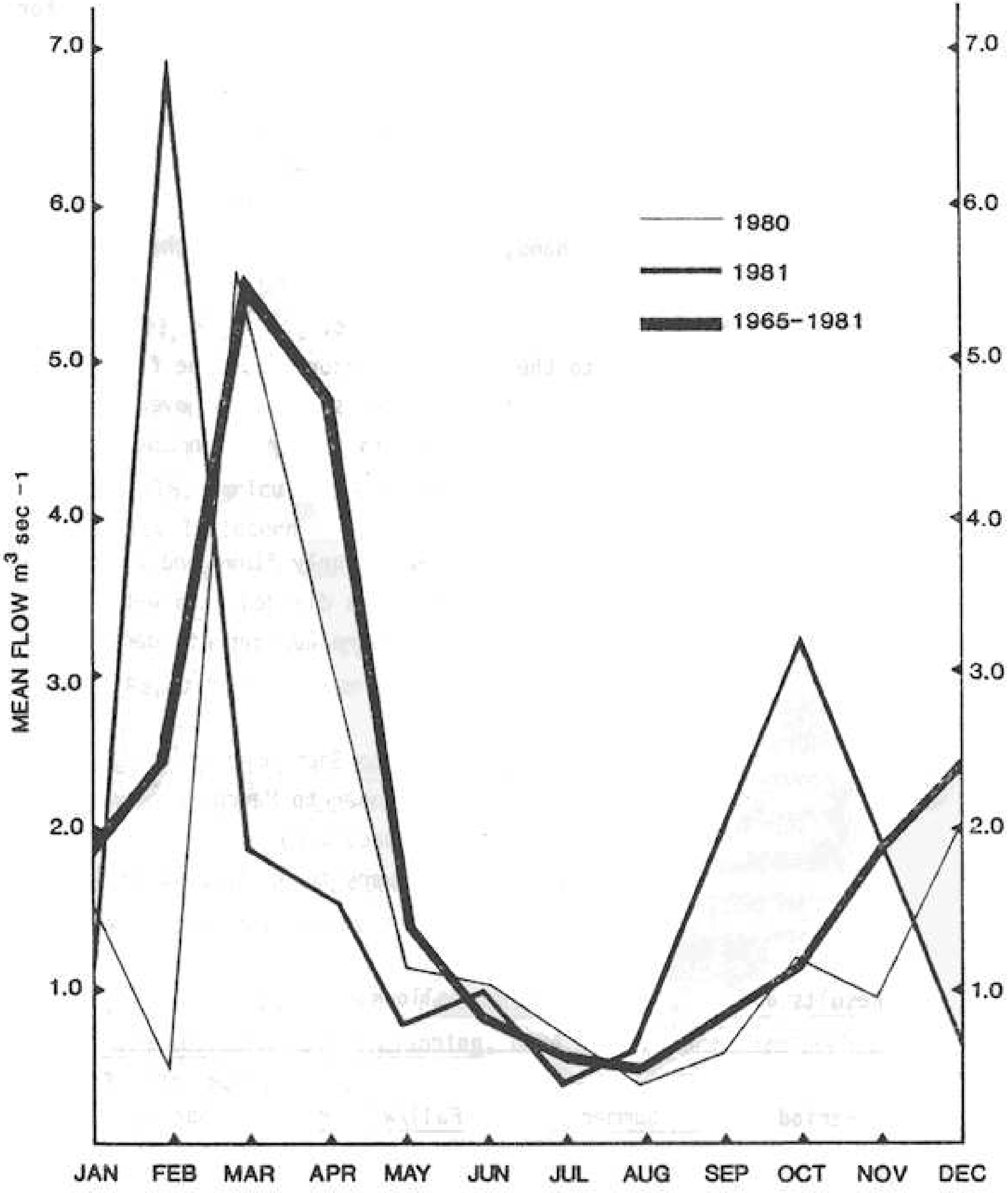

FIGURE A1: Monthly Flows At Station 10 (1980, 1981, 1965 - 1981)

Summer wet weather flows account for 17.7% of annual wet weather/runoff flows at station 10.

To facilitate an analysis of phosphorus flux at various monitoring stations, flow volumes were estimated by area pro-rating of station 10 flows. Simple area pro-rating was applied to wet weather flows. Dry weather flows, however, were measured net of urban contributions and pro-rating was based on the rural areas in each catchment.

This was done because dry weather flows from the urban area*, 0.3 m^3sec^{-1}, were so predominant that simple pro-rating would have been erroneous. The WPCP dry weather flow is 0.2 m^3sec^{-1}. The remaining urban flow, 0.1 m^3sec^{-1} is associated with a storm sewered area measuring 13.57 km^2. In contrast to this, the rural portion of the station 10 mean dry weather flow, 0.05 m^3sec^{-1} is generated by an area measuring 144 km^2.

For the monitoring stations of interest, areas and summer flow volumes are as follows:

Station	Upstream Area (km^2)		Summer Flow Volume (10^3m^3)	
	Total	urban	dry	wet
1	30		86	1500
3	54		154	2700
6	100	8	866	5001
7	119	13	2590	5952
10	144	14	2870	7202
13	161	14	2920	8052

The annual wet weather flow volume at station 13 is 45,400 m^3. The summer wet weather volume comprises 17.7% of this. This percentage value is used in the seasonal allocation of certain runoff associated annual phosphorus loads.

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* SAREMP Technical Report U-3.

APPENDIX 2:SEASONAL WATER QUALITY DATA

TABLE A2-1: Total Phosphorus (mg/L)

STATION	STATISTIC	SUMMER		FALL AND WINTER	SPRING RUNOFF
		dry	wet		
1	mean	.035	.060	.051	.156
	min.	.026	.030	.024	.040
	max.	.046	.136	.150	.350
	no. obs.	8	8	9	7
3	mean	.044	.064	.075	.131
	min.	.034	.034	.030	.050
	max.	.058	.121	.290	.280
	no. obs.	9	11	9	5
6	mean	.078	.091	.069	.145
	min.	.040	.062	.034	.054
	max.	.114	.136	.144	.222
	no. obs.	9	8	9	6
7	mean	.142	.149	.303	.498
	min.	.050	.080	.090	.138
	max.	.330	.280	1.280	1.350
	no. obs.	9	11	9	7
10	mean	.101	.120	.173	.223
	min.	.055	.055	.045	.088
	max.	.160	.218	.500	.345
	no. obs.	9	8	9	5
13	mean	.060	.109	.094	.224
	min.	.013	.054	.018	.082
	max.	.108	.334	.335	.360
	no. obs.	9	11	8	7

TABLE A2-2: Soluble Phosphorus (mg/L)

STATION	STATISTIC	SUMMER		FALL AND WINTER	SPRING RUNOFF
		dry	wet		
1	mean	.005	.017	.017	.054
	min.	.001	.003	.004	.002
	max.	.013	.052	.051	.097
	no. obs.	8	8	9	7
3	mean	.009	.018	.026	.045
	min.	.007	.003	.010	.003
	max.	.012	.048	.049	.096
	no. obs.	9	11	9	5
6	mean	.005	.009	.015	.050
	min.	.001	.001	.001	.003
	max.	.029	.057	.037	.099
	no. obs .	9	8	9	6
7	mean	.049	.051	.221	.208
	min.	.001	.002	.043	.056
	max.	.129	.146	1.180	.415
	no. obs.	9	11	9	7
10	mean	.024	.032	.113	.122
	min.	.004	.002	.004	.062
	max.	.053	.109	.440	.205
	no. obs .	9	8	9	5
13	mean	.015	.030	.075	.129
	min.	.001	.006	.001	.049
	max.	.039	.064	.310	.230
	no. obs .	9	11	8	7

TABLE A2-3: Suspended Sediment (mg/L)

STATION	STATISTIC	SUMMER		FALL AND	SPRING
		dry	wet	WINTER	RUNOFF
1	mean	3.1	8.2	14.6	35.2
	min.	1.3	1.9	1.2	6.5
	max.	6.5	25.0	38.2	122.6
	no. obs.	6	8	9	7
3	mean	5.8	10.6	34.7	30.2
	min.	2.5	3.2	3.1	10.7
	max.	11.5	37.0	205.0	76.0
	no. obs.	7	11	9	5
6	mean	9.6	14.2	37.8	31.5
	min.	5.1	10.5	11.2	6.2
	max.	13.7	18.0	63.8	168.6
	no. obs.	7	8	6	9
7	mean	7.1	9.4	15.8	58.0
	min.	2.6	4.9	2.4	27.1
	max.	12.5	15.0	94.1	115.1
	no. obs.	7	11	9	7
10	mean	8.5	10.9	11.1	27.7
	min.	4.0	5.6	1.1	8.3
	max.	13.3	22.1	37.2	51.7
	no. obs.	7	8	9	5
13	mean	5.5	17.7	2.8	21.8
	min.	0.1	3.3	0.7	4.9
	max.	11.2	101.0	7.0	41.3
	no. obs.	6	11	8	7

STRATFORD-AVON RIVER ENVIRONMENTAL MANAGEMENT PROJECT
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S-2	Physical Characteristics of the Avon River
S-3	Water Quality Monitoring of the Avon River - 1980, 1981
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S-5	Experimental Efforts to Aerate the Avon River with Small In-stream Dams
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