Pigeon Lake Phosphorus Runoff Modelling

Final Report – Current Conditions, Development, & Restoration Scenarios

July 25, 2017

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This report was produced as part of the Ecosystem Services Assessment for Environmental Innovation and Competitiveness project (ESA). This project is led by the Alberta Biodiversity Monitoring Institute, and is a joint effort with Alberta Innovates – Technology Futures, Silvacom, Green Analytics, and the University of Alberta.

Core funding for this project was supplied by Alberta Innovates – Bio Solutions, the Alberta Livestock and Meat Agency, and Alberta Innovates – Technology Futures

Contents

Introduction

Pigeon Lake is a major recreational lake in central Alberta that is regularly subjected to blue-green algae warnings in summer months. To address these water quality issues, the Pigeon Lake Watershed Association is developing a Pigeon Lake Watershed Management Plan (www.plwmp.ca) to develop recommendations for watershed policies and practices to improve the long-term health of the watershed. Phosphorus inputs to the lake have been identified as the critical factor leading to blue-green algae blooms, and previous efforts have sought to understand the sources of phosphorus to the lake; specifically, the Pigeon Lake Phosphorus Budget (Teichreb 2014) estimated the amount of phosphorus entering Pigeon Lake from external sources, including sewage, groundwater, precipitation, streams, and runoff. While useful for understanding what sources should be targeted to reduce phosphorus loading, the methodology used in the phosphorus budget is not appropriate for evaluating how future landcover conditions may influence non-point source phosphorus input. In contrast, ABMI's water purification model is designed to address this type of problem, but is a regional model rather than a local model informed by conditions at Pigeon Lake itself. Therefore, the two principal goals of this study were to 1) compare the results of ABMI's water purification model to the existing Pigeon Lake Phosphorus Budget in order to ensure its suitability for the watershed, and 2) assess how phosphorus loading from surface runoff may change as a result of alternative landscape development and restoration scenarios.

Methods

Detailed methods on ABMI's water purification model area available in Habib et al. (2016). The original ABMI model is a regional model that uses an 800m cell size, but the model was adjusted to run at a 100m cell size, solely within the Pigeon Lake watershed.

Model Setup

The ArcGIS Hydrology toolbox (Spatial Analyst extension) was used to create the stream network used in the model, based on the Alberta Base layer 100m DEM, using the following steps:

1. *Fill* – this tool fills small sinks within the DEM, such that the resulting DEM is completely hydrologically connected, with no local depressions.
2. *Flow Direction* – creates a raster showing the direction of water flow from each cell to its steepest downslope neighbour.
3. *Flow Accumulation* – based on the flow direction raster, this tool creates a raster showing the cumulative number of cells that flow into each cell from upslope.

Creating a river network from the flow accumulation raster requires setting a threshold value, above which all cells would be considered rivers; after testing a number of values, a threshold of 120 was selected. This threshold reasonably approximates the stream network depicted in the Alberta Base Layer "SLNET" (Figure 1). The stream drainages corresponding to this derived stream network is depicted in Figure 2.

Runoff Modelling

ABMI's water purification model is designed to simulate annual precipitation, overland flow, and surface flow of water. ABMI's enhanced landcover and human footprint layers, as well Agriculture and Agri-Food Canada's (AAFC) annual crop type map, were used to represent the landscape; all landcover layers were based on 2012 conditions (Figure 3; summary of landcover by stream drainage is available in Additional Table 2). Phosphorus loading is calculated using nutrient export coefficients for each landcover type derived by Donahue (2013; see Additional Table 3 for full list of export coefficients).

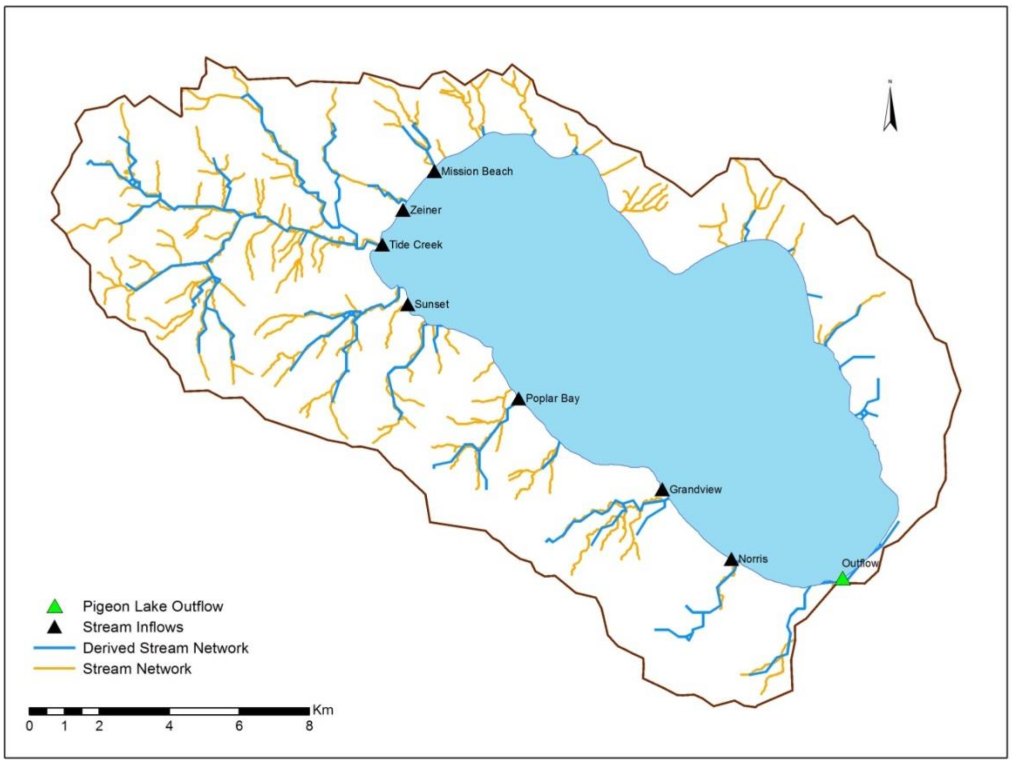

Figure 1. Comparison of streams obtained from Alberta Base Layers (orange lines), and those derived from a 100m digital elevation model (blue lines).

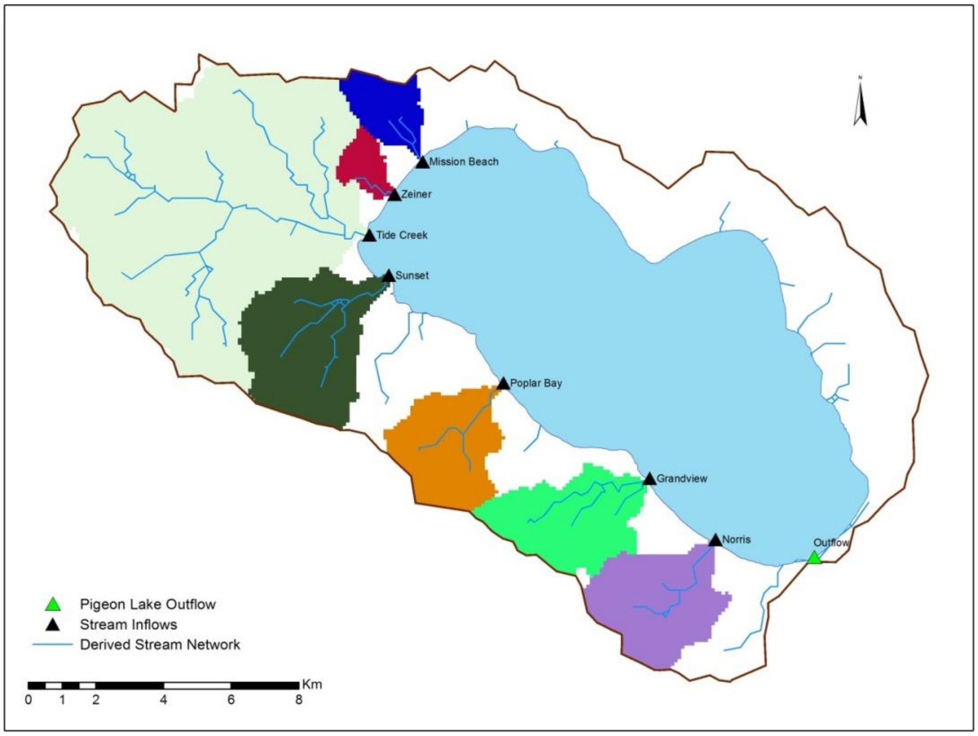

Figure 2. Stream drainage areas in the Pigeon Lake watershed.

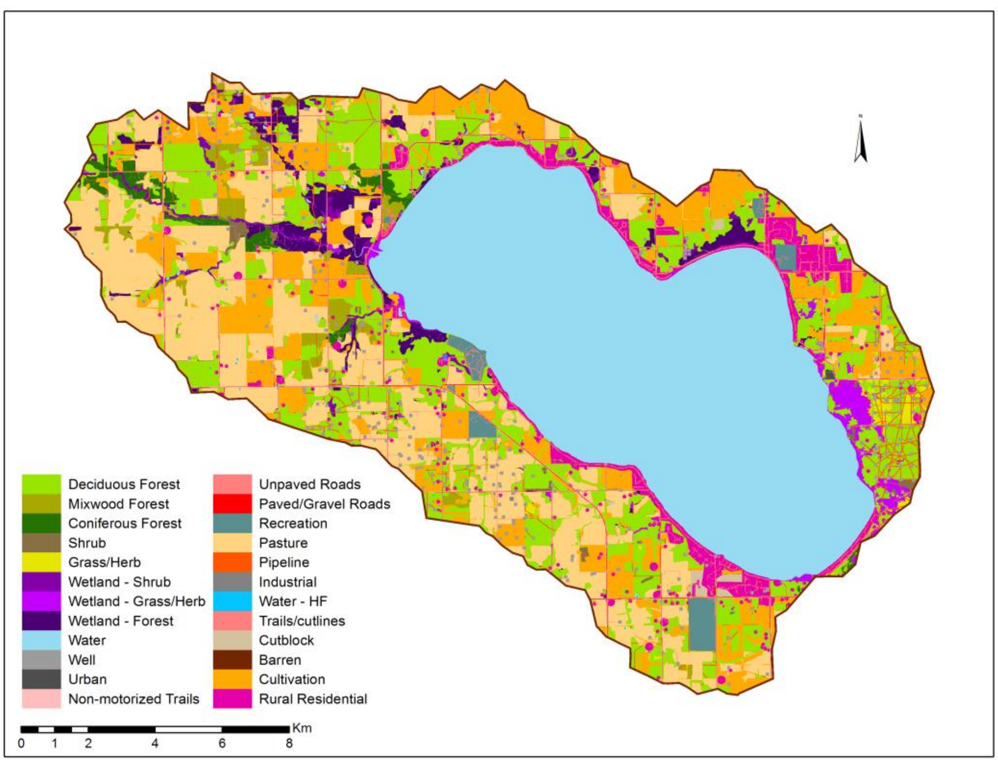

Figure 3. Landcover in the Pigeon Lake watershed, based on 2012 conditions.

Landscape Scenarios

Development Scenarios

The water purification model was run under alternative landscape scenarios to assess current, historical, and potential future phosphorus loading to Pigeon Lake. Current conditions were based on ABMI's 2012 enhanced vegetation landcover map, which is the most current comprehensive landcover layer available. To assess historical conditions, all human development present on the landscape was replaced with coniferous forest, which is the most likely pre-development landcover in this area (Don Davidson, pers. comm); Although it is unlikely that the entire region would be the same forest type, the model parameters for different undeveloped landcover types (i.e. grassland, shrubland, and coniferous and deciduous forest) are similar enough (Donahue 2013) that the outcome of this modelling scenario will not be strongly affected.

Future landcover scenarios included both new rural residential and summer village development, and/or restoration of riparian buffers. The location and intensity of new development was based on Leduc County's North Pigeon Lake Area Structure Plan (Leduc County 2011) and the County of Wetaskiwin Pigeon Lake Watershed Area Concept Plan (County of Wetaskiwin 2014), and includes high- and low-intensity rural residential development, mixed use (i.e. mostly a continuation of existing agricultural land-use, with some residential development), recreation, and development within areas already zoned as summer villages (Figure 4). Because there are no fixed rates of development in each zone, 4 future landscapes were created representing low, moderate, high, and very high levels of future development (Table 1).

New developments were simulated on a quarter-section basis, as this is the level at which land ownership and development decisions are typically made; that is, either an entire quarter-section would be converted to residential, or none of it would be. The breakdown of landcover in newly converted quarter-sections was based on existing subdivision within the watershed, comprising 90% rural-residential (which includes houses, lawns, and trees), 5% paved roads, and 5% unpaved roads. Development was simulated probabilistically, such that a quarter-section in a zone with a (for example) 30% rate had a 30% probability of being developed; therefore, the actual development rates in a given simulation will not exactly match the rates presented in Table 1. An example of a future landcover map under "High" development is depicted in Figure 5. In all 4 scenarios, the restoration and recreation zones specified in the Leduc Area Structure Plan (Leduc County 2011), as well as areas already zoned as summer villages (Figure 4) were also converted to forest, recreation, and rural residential landcover types, respectively.

Riparian restoration was modelled by identifying all cells that contain part of the derived stream network and converting their landcover to forest. Because the cell size is 100m, this approximates a 50m riparian buffer on each side of the stream. Each of the 5 landscape scenarios (the 4 development scenarios plus the current landscape) was run both with and without riparian restoration, for a total of 10 landscape scenarios. Because future development was simulated probabilistically, each of the 10 landscape simulations was replicated 5 times to obtain a range of results.

Table 1. Residential development rates under 4 alternative future development scenarios.

Development Scenario	Residential - High Development Probability	Future Zoning Residential – Low Development Probability	Mixed Use
Low	30 %	15 %	5 %
Moderate	40 %	20 %	10 %
High	60 %	30 %	15 %
Very High	75 %	50 %	25 %

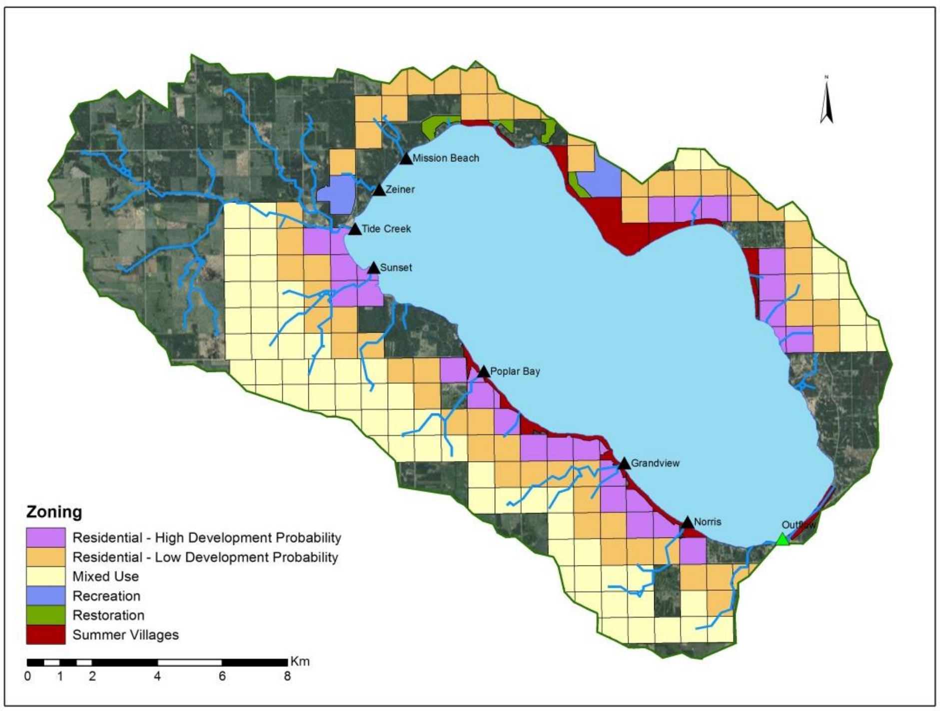

Figure 4. Zoning for future development in the Pigeon Lake watershed, based on plans from Wetaskiwin and Leduc Counties.

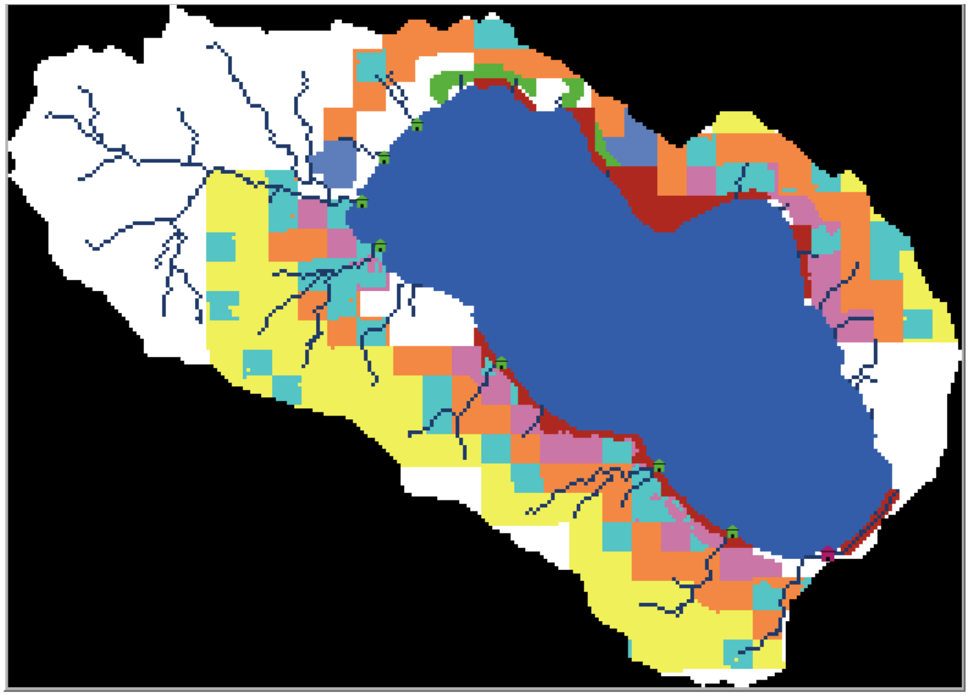

Figure 5. Example landcover map showing potential future residential development under the “high development” scenario. Colours match the zoning depicted in Figure 4, with newly developed quarter-sections shown in teal.

Reforestation Scenarios

In addition to simulating future development, the model was also run under hypothetical reforestation scenarios in which agricultural land was converted to forest. Agricultural land, including both annual cropland and tame pasture, was prioritized for reforestation based on the amount of phosphorus it supplied to Pigeon Lake in the baseline model run. Ten reforestation scenarios were conducted at increasing levels of land conversion; this was accomplished by setting a “phosphorus supply threshold” based on the baseline model run, and all agricultural landcover within cells over the threshold were converted to forest. All other landcover types within these cells were unchanged. By iteratively increasing the phosphorus supply threshold, reforestation scenarios were “nested” such that each run reforested all of the land from the previous scenario, plus any additional land over and above the new phosphorus threshold. The total amount of reforested land and the total phosphorus load to Pigeon Lake were recorded for each reforestation scenario.

Results

The existing lake budget delineated phosphorus inputs from a variety of sources, including stream inflows (of both measured and unmeasured streams), overland inflow, dustfall/precipitation directly to the lake surface, groundwater, and sewage. ABMI's model only estimates surface runoff, so the comparison was restricted to the sum of Teichreb's estimates for stream and overland inflows (3290 kg/year; Table 5-1 in Teichreb 2014). In the current landscape analysis, surface inputs to the lake were estimated to be 3707 kg phosphorus/year entered Pigeon Lake through overland and stream inflows (Figure 6); this represents a difference of 12.7% compared to Teichreb's (2014) finding of 3290 kg/yr of phosphorus. In contrast, phosphorus loading in the pre-development landscape was 1129 kg/year, representing an approximately 70% decrease compared to current conditions (Figure 7).

Development Scenarios

Simulated future development increased the amount of phosphorus supplied to the lake by between 19% (low development scenario) and 39% (very high development scenario); an example of the "high development" scenario is depicted in Figure 8. Model runs with riparian restoration but no future residential development showed a 17% reduction in phosphorus supplied to the lake. When combined with future development, riparian restoration buffered the effects of the additional developed land-use, such that the amount of phosphorus supplied to the lake did not change dramatically relative to current landcover conditions (range: 2% decrease to 3% increase). A comparison of phosphorus supplied to Pigeon Lake under each land-use scenario is depicted in Figure 9. The breakdown of phosphorus inputs by stream drainage under current and pre-development scenarios is presented in Additional Table 2 at the end of this document.

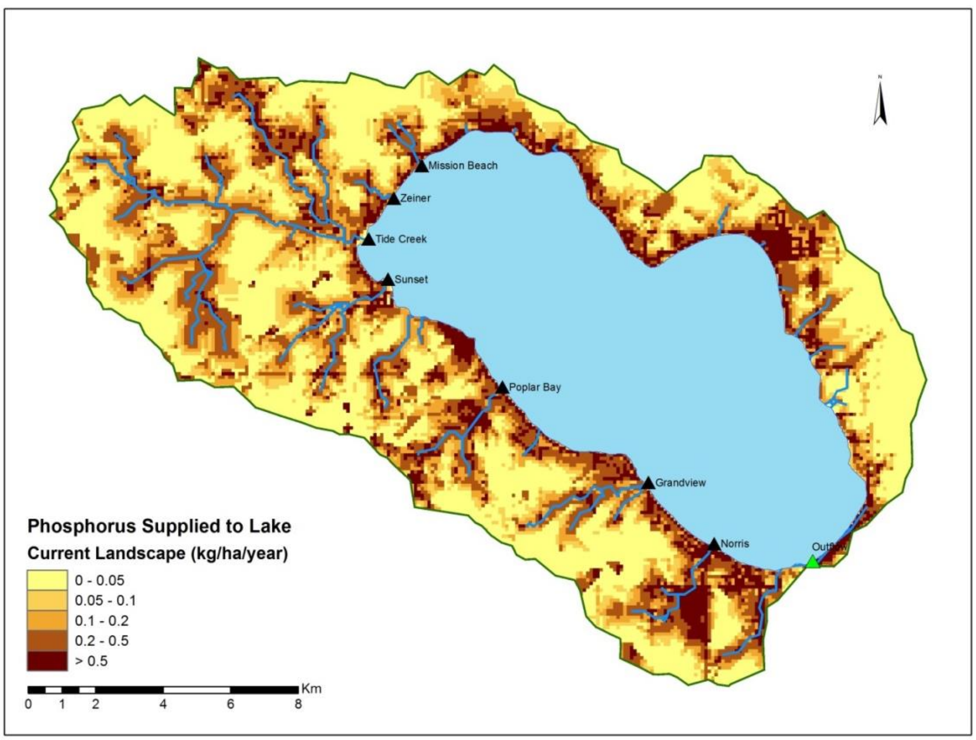

Figure 6. Modelled phosphorus supplied to Pigeon Lake by the surrounding watershed, based on current (2012) landcover conditions.

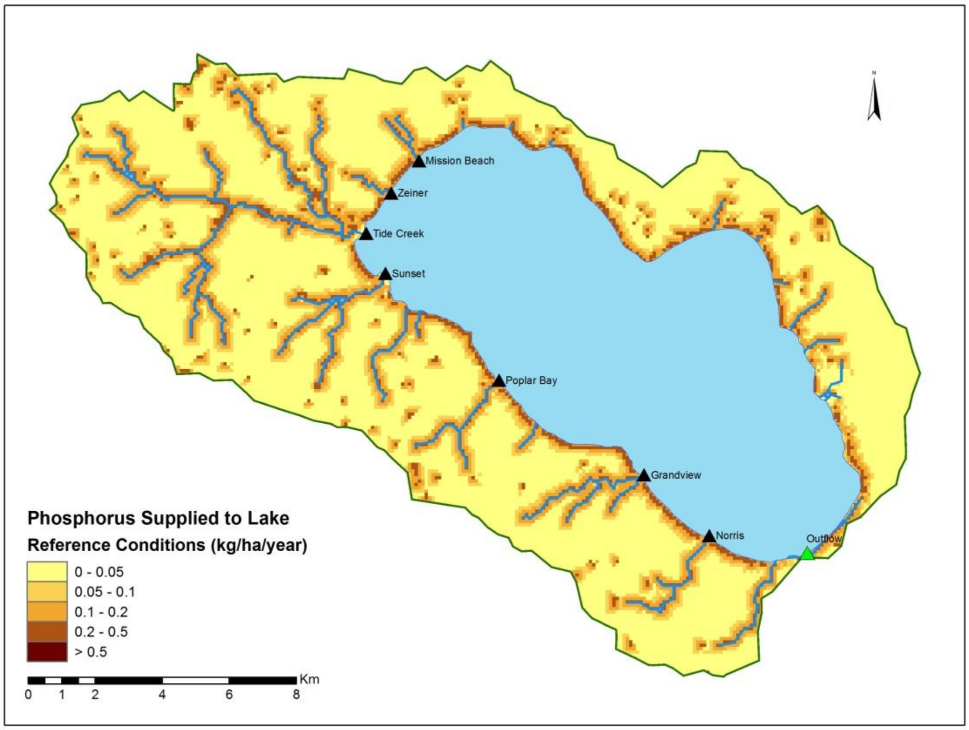

Figure 7. Modelled phosphorus supplied to Pigeon Lake by the surrounding watershed, based on pre-development conditions.

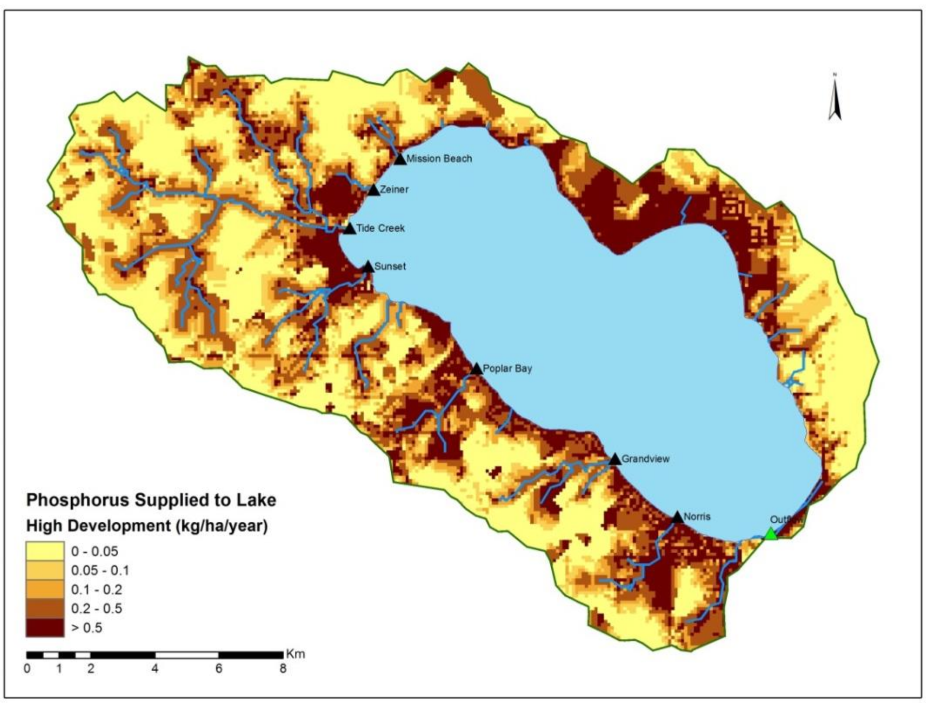

Figure 8. Modelled phosphorus supplied to Pigeon Lake by the surrounding watershed, based on the simulated “high development” scenario.

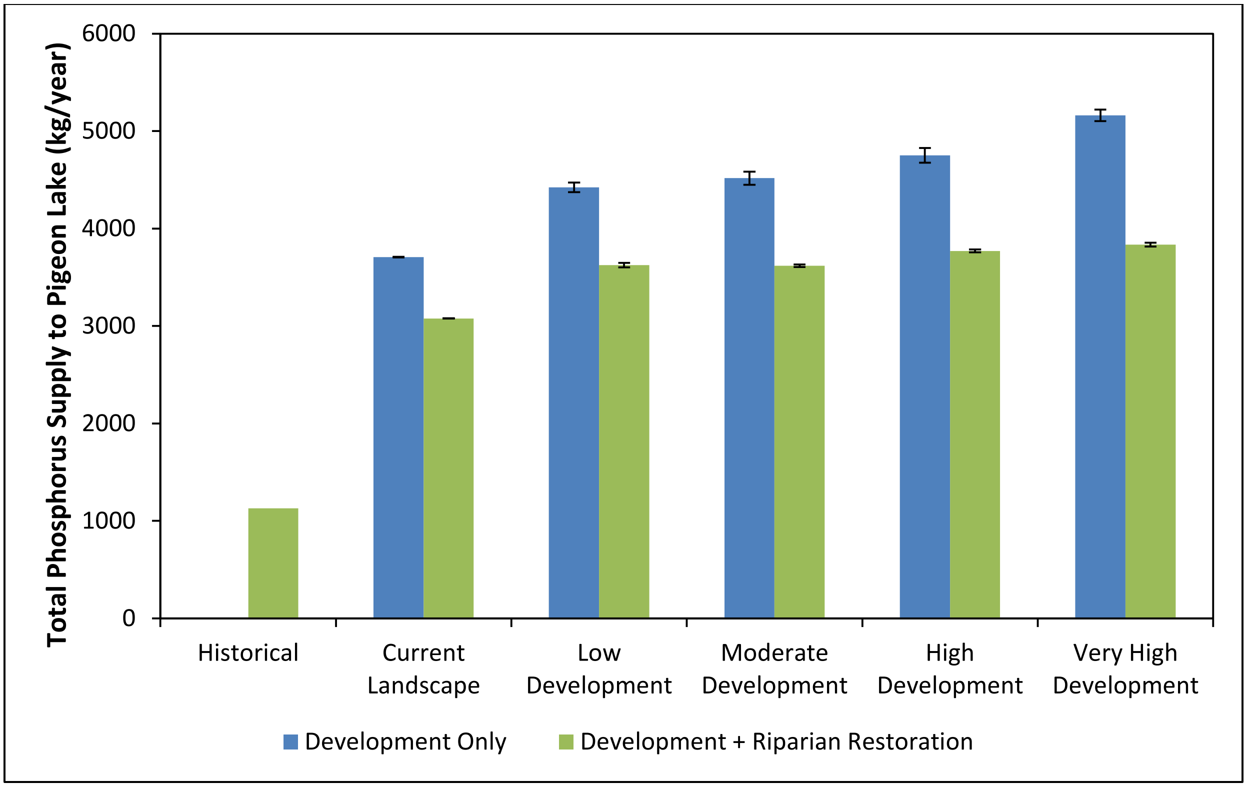

Figure 9. Modelled phosphorus supplied to Pigeon Lake based on current, historical, and potential future land-use scenarios.

Reforestation Scenarios

Reforesting increasing amounts of agricultural land led to diminishing returns for phosphorus reductions to Pigeon Lake (Figure 10). To some extent this was expected, given that areas supplying the most phosphorus were prioritized for reforestation. However, Figure 10 suggests that after a certain point, there is almost no additional reduction in phosphorus runoff to be gained from reforesting more agricultural land. A map showing the priority areas for reforestation, corresponding to the mid-point of Figure 10 where large phosphorus reductions stop (white data point), is depicted in Figure 11. This represents reforesting approximately 30% of the agricultural land in the Pigeon Lake watershed.

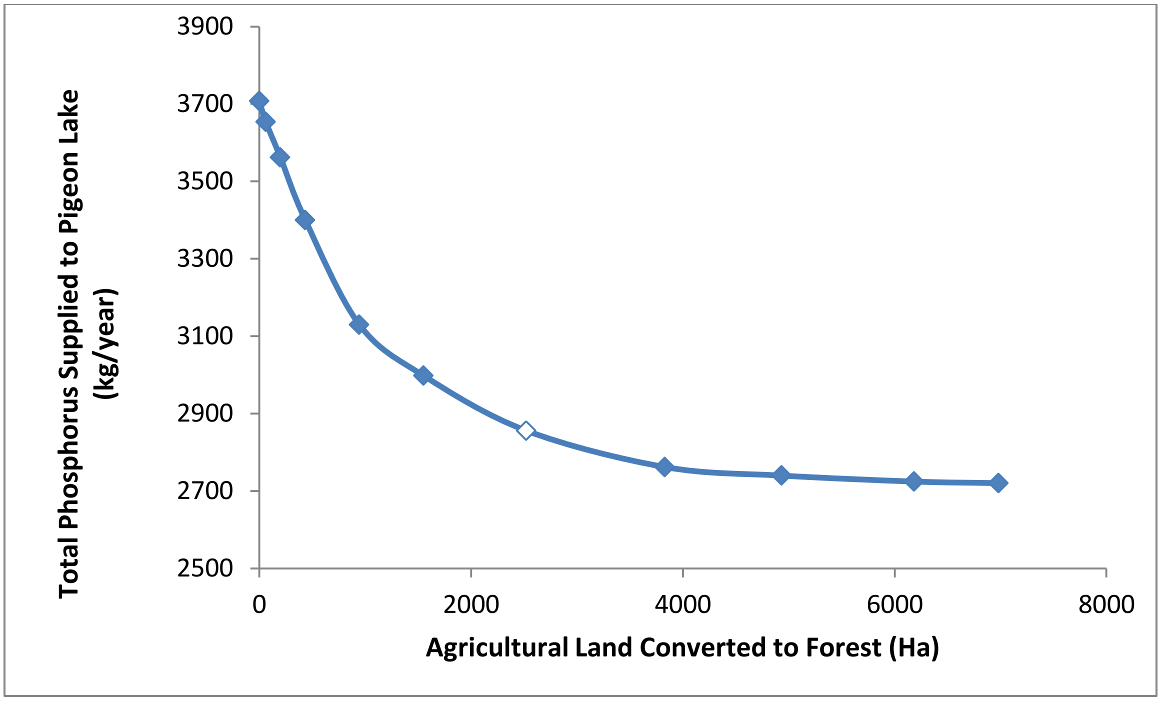

Figure 10. Phosphorus supplied to Pigeon Lake under hypothetical alternative reforestation scenarios. The white data point represents the reforestation scenario depicted in Figure 11.

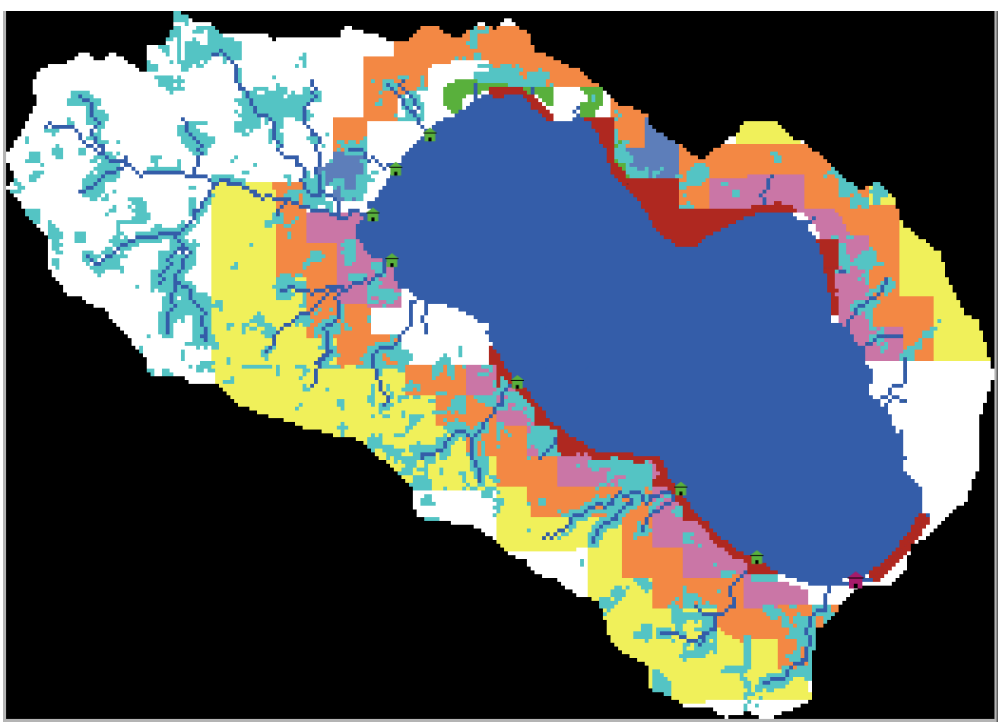

Figure 11. Hypothetical reforestation (teal cells) of agricultural land in the Pigeon Lake watershed, targeting moderate-to-high phosphorus source areas. Note that only agricultural landcover types (pasture and cropland) in teal cells were reforested; other landcover types were unchanged.

Discussion

This estimate of phosphorus under current landcover conditions is higher than Teichreb's (2014) estimate, with a difference of about 12.7%. Both methods relied on applying nutrient export coefficients to landcover data in the basin. This analysis used a considerably more detailed landcover layer; the provincial base layer used by Teichreb had 9 categories for terrestrial land cover, while the ABMI model used 18 categories. Most of the additional categories in the ABMI layer are human footprint features (e.g. roads, trails, cutblocks) that are grouped together as "developed" in the simpler landcover layer.

A model is a simplification of reality; the purpose of this work is not to perfectly replicate field conditions, but rather to understand the general pattern of phosphorus loading within the watershed. Therefore, although the current model predicts a higher amount of phosphorus loading, both estimates are on the same order, which suggests that this tool is appropriate for understanding the relative contribution of phosphorus loading across the watershed, as well as how land management changes will influence it. The principal goal of the scenario modelling in this report was to assess how phosphorus supplied to Pigeon Lake has changed compared to historical conditions, how future residential development will affect phosphorus loading, and whether the effects of increased development could be mitigated by restoring riparian areas throughout the watershed.

In the historical scenario, phosphorus loading was estimated to be 70% lower than current conditions. While dramatic, this result is not surprising, given how much land-use change and development has occurred in the watershed. The reference condition should not be taken to be a realistic objective, but rather as a baseline to provide context for current and future conditions.

Interestingly, the development scenarios that included riparian restoration suggested that restoring these areas would be sufficient maintain similar phosphorus loading to current conditions, even in the face of additional phosphorus supplied by increased development. While this is an encouraging finding, there are two principal caveats: first, ecological restoration of fully functional riparian areas in currently degraded regions may not be completely successful. And second, the model simulates nutrient retention using a constant retention parameter for each landcover type; that is, no matter how much phosphorus runoff flows over a given patch of land (i.e. a riparian buffer), nutrients will be retained at the same rate. This can be seen in Figure 9, where the difference in phosphorus supply between restored- and un-restored landscapes at each level of development (i.e. the gap between the blue and green bars in each pair) increases with more intensive development; put simply, the more phosphorus there is in overland flow, the more phosphorus there is to be retained in riparian areas. However, in reality, there may be a limit on a parcel of land's capacity to retain nutrients, in which case these results would underestimate the amount of phosphorus supplied to Pigeon Lake as development increases.

Given that the benefits of restoration are likely overestimated, the results in Table 1 suggest that the best-case scenario would be that riparian restoration would "cancel out" the effects of future development, maintaining phosphorus inputs at approximately current conditions; at worst, there will be a significant increase in phosphorus relative to today. Therefore, this modelling work creates a hypothesis to be tested as development proceeds, for example as a before-after control-impact (BACI) study. In such a study, areas slated for development and restoration would be identified, and extensive water sampling would be done both before and after the development occurs, along with water monitoring at adjacent sites not subject to future development to correct for watershed-wide factors such as climate.

The reforestation scenarios demonstrate one possible strategy to reduce phosphorus loading to Pigeon Lake. Reforesting agricultural land would be costly, both in terms of the actual cost of conducting a landcover change of this magnitude, as well as the opportunity cost of foregone agricultural revenue. Therefore, these scenarios represent an exploration of methods to significantly reduce phosphorus, putting aside considerations of logistical and economic feasibility; put another way, the goal of the reforestation analysis is to determine the bounds of what could be possible in terms of phosphorus reduction. Even this widespread reforestation of approximately 2500 hectares of agricultural land – representing nearly one-third of the agricultural land in the Pigeon Lake basin – only led to 23% reduction in phosphorus supplied to Pigeon Lake (white data point in Figure 10). Thus, addressing the remaining gap between the baseline and historical landscape conditions would require considerable reductions in phosphorus loading from other landcover types, including the developed areas along the lakeshore highlighted as important sources of phosphorus in Figure 6.

Limitations

Like any model, there are several assumptions that can affect the output; two aspects in particular should be discussed. First, as water moves to adjacent cells during overland flow, a portion of the phosphorus contained in runoff is removed in each cell. The percentage removed is tied to landcover, and these nutrient retention parameters have a great deal of influence over model output. Once runoff reaches a cell defined as a stream, no further nutrient retention occurs; therefore, the second factor is the length of surface flow from the origin cell to the nearest stream (measured in number of cells traversed). This cannot be easily adjusted in the same way as the retention parameters, but instead is a direct result of the flow accumulation threshold used to define the stream network (see *Model Setup* section in Methods & Results above). While the derived stream network aligns reasonably well with the provincial base layer (Figure 1), the base layer itself is only an approximation of on-the-ground conditions that can fluctuate with wet and dry years. Care should be used in interpreting model predictions, particularly in two ways. First, the relative changes in phosphorus loading will be more reliable than specific numeric values. And second, although the model runs at a relatively fine-resolution 100m cell size, overland water flow routing in the model is greatly simplified, therefore results should be interpreted at a larger geographic scope than individual cells (e.g. stream drainages).

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Additional Tables

Table 2. Distribution of landcover types across the stream drainages of the Pigeon Lake watershed.

Name	TOTAL AREA	Barren	Cutblock	Forest	Wetland Forest	Wetland Shrub	Wetland Grass	Agriculture	Grass	Shrub	Roads
Grandview	1044.1	0.0	0.4	290.3	4.2	0.0	6.2	193.5	11.7	8.7	9.7
Mission Beach	409.2	0.0	0.0	148.6	19.4	0.5	0.0	77.9	1.7	0.0	6.5
Norris	1078.5	0.0	32.6	241.0	0.9	0.0	0.6	147.3	3.4	4.3	18.1
Poplar Bay	923.2	0.0	0.9	220.4	1.5	0.0	0.4	200.6	0.1	0.1	8.0
Sunset	1397.9	0.0	0.0	453.0	29.0	21.2	3.9	255.4	0.7	4.7	11.6
Tide Creek	5739.8	0.5	0.0	1492.9	381.4	147.0	18.4	1085.0	4.4	46.0	47.7
Zeiner	212.4	0.0	0.0	132.3	17.9	3.0	0.2	28.6	0.0	0.0	5.4
Non-Stream	7441.3	0.0	30.2	2156.1	206.6	42.6	297.9	1639.1	119.3	36.6	171.6
TOTAL	**18246.5**	**0.5**	**64.1**	**5134.6**	**660.7**	**214.4**	**327.5**	**3627.4**	**141.2**	**100.4**	**278.7**

Name	Industrial	Pasture	Pipelines	Recreation	Rural Residential	Seismic Lines	Motorized Trails	Non-motorized Trails	Urban	Wellpads
Grandview	0.6	442.8	3.7	0.0	17.3	4.2	10.2	15.3	0.0	22.8
Mission Beach	0.0	102.7	6.7	0.0	24.2	2.0	4.4	9.6	0.0	3.5
Norris	0.0	354.2	10.4	123.1	84.9	2.6	15.1	26.6	0.0	11.5
Poplar Bay	1.0	336.0	12.2	47.9	16.0	2.6	20.3	13.3	0.0	40.4
Sunset	0.0	475.7	18.8	0.0	32.6	7.1	18.0	21.7	0.0	37.1
Tide Creek	0.8	2151.5	35.5	0.0	60.7	25.8	31.8	89.4	0.0	91.2
Zeiner	0.0	9.9	0.0	1.1	2.3	1.4	0.7	8.2	0.0	1.0
Non-Stream	3.7	1002.8	132.1	129.8	890.7	30.8	115.3	262.5	6.9	144.7
TOTAL	**6.1**	**4875.6**	**219.3**	**301.9**	**1128.8**	**76.4**	**215.8**	**446.6**	**6.9**	**352.3**

Table 3. Phosphorus export coefficients by landcover type. Based on Donahue (2013).

Landcover	Phosphorus Export Coefficient (kg/ha/mm precipitation)	Landcover	Phosphorus Export Coefficient (kg/ha/mm precipitation)
Agriculture – Flat	0.00096	Pipelines	0.00201
Agriculture – Rolling	0.00122	Recreation	0.00187
Agriculture – Hilly	0.00151	Rural Residential	0.00026
Barren	0.000251	Seismic Lines	0.00101
Cutblock	0.000763	Shrubland	0.000834
Forest	0.00061	Motorized Trails	0.01211
Grass	0.00013	Non-motorized Trails	0.00447
Roads	0.00314	Urban	0.00178
Industrial	0.00184	Wellpads	0.00689
Pasture	0.00086		

Table 4. Breakdown of annual phosphorus supply to Pigeon Lake by stream drainage under alternative future development and restoration scenarios, measured in kg/year. Each value is the mean of 5 simulations for each level of development; standard deviations are provided in parentheses.

	Historical	Development Only					Development + Riparian Restoration				
		Current	Low	Moderate	High	Very High	Current	Low	Moderate	High	Very High
Mission Beach	21	60 (0.3)	72 (24.6)	78 (25.4)	71 (25.1)	103 (44.3)	43 (0.3)	56 (8.2)	48 (8)	50 (7.3)	48 (12.7)
Grandview	57	117 (0.7)	171 (33.8)	136 (20.8)	162 (50.1)	238 (75.7)	92 (0.8)	89 (14.4)	94 (4.1)	90 (7.5)	85 (5.2)
Zeiner	13	26 (0.1)	32 (0.7)	32 (0.3)	33 (0.2)	47 (14.2)	21 (0.1)	23 (2.4)	22 (2.8)	22 (2.7)	21 (2.8)
Sunset	77	198 (0.5)	214 (15.6)	244 (16.5)	238 (20.5)	346 (20.3)	152 (0.3)	150 (5.9)	147 (14.5)	162 (16)	155 (19.6)
Norris	40	253 (1.5)	266 (25.6)	275 (24.9)	315 (51)	297 (10.2)	145 (0.7)	149 (5.5)	155 (8.1)	152 (4.2)	153 (8.6)
Poplar-Bay	42	205 (2)	230 (23.7)	219 (10.5)	225 (2.6)	241 (21.1)	136 (0.2)	137 (6.5)	134 (7.3)	137 (8.3)	137 (5.6)
Tide-Creek	323	732 (1.7)	773 (23.9)	786 (27)	816 (40.7)	838 (47.3)	543 (0.9)	561 (14.8)	549 (5.1)	569 (4.2)	568 (7.1)
Direct Loading[1]	387	1571 (7.4)	2052 (95.2)	2080 (39.3)	2187 (17.3)	2282 (45.3)	1572 (4.5)	2084 (50.1)	2103 (29.6)	2218 (14.6)	2295 (32)
TOTAL[2]	**1129**	**3707 (5.4)**	**4423 (108.5)**	**4516 (148.8)**	**4751 (167.5)**	**5162 (132.9)**	**3078 (0.9)**	**3625 (49.1)**	**3617 (29.1)**	**3771 (33.6)**	**3836 (44.8)**

[1]Non-stream contributions that enter the lake directly

[2]Includes inputs from streams listed above, direct loading to the lake, as well as inputs from unlisted/unnamed streams.