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Spokane County Department of Utilities
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Spokane, Washington 99260-0430

Attention Ben Brattebo
Water Resources Specialist

Subject: Technical Memorandum
Preliminary Groundwater Loading Analyses – Lake Spokane
Bi-State Nonpoint Source Phosphorus Study
File No. 0188-135-01

INTRODUCTION

In our technical memorandum entitled *Groundwater Loading Analyses - Orthophosphate, Bi-State Nonpoint Source Phosphorus Study* and dated January 29, 2009, GeoEngineers presented results of preliminary analyses estimating the loading of total phosphorus and orthophosphate to the Spokane River and its tributaries from groundwater. Groundwater loads were calculated for reaches where sufficient existing data were available, which included the mainstem Spokane River upstream of Nine Mile Dam, the Little Spokane River, and Hangman Creek. This simplified analysis was performed by comparing baseflow contributions associated with gaining stream segments with phosphorus concentrations in groundwater adjacent to those reaches.

The preliminary groundwater loading analyses summarized in this memorandum were performed as a component of Task 3 of the Phase 1 Supplement of the Bi-State Nonpoint Source Phosphorus Study (NPS Study) and supplement previous analyses (GeoEngineers, 2009 and 2010). Herein, we summarize results of our analyses estimating the loading of total phosphorus (attached Table 1) and orthophosphate (attached Table 2) into Lake Spokane from nearshore unconsolidated aquifers. Soluble reactive phosphorus primarily consists of orthophosphate and refers to the dissolved phosphorus component generally available for biological uptake. Therefore, orthophosphate analysis is appropriate for use in the evaluation of the quantity of phosphorus transported by groundwater that supports biologic activity in Lake Spokane.

Our analyses are largely based on data presented by Soltero et al. (1992). We anticipate that these preliminary results will be useful as Spokane County, the Nonpoint Advisory Committee, and the GeoEngineers consultant team evaluate where project data collection funding is best allocated.

BASEFLOW

The geometry and flow characteristics of nearshore unconsolidated aquifers adjacent to Lake Spokane is complicated by numerous zones of shallow bedrock and/or other low-permeability formations, creating numerous hydraulically distinct unconsolidated aquifers on both the north and south sides of Lake Spokane. Soltero et al. (1992) reports significant variation in groundwater flow direction depending on location and reservoir stage.

To simulate the geometry and hydraulic characteristics of the groundwater/surface water interface around Lake Spokane, Soltero et al. (1992) divided the shoreline of Lake Spokane into 41 straight-line segments. A total of 21 segments are situated along the north lakeshore (N1 through N21) and 20 along the south lakeshore (S1 through S20). The locations of lakeshore segments are presented in Appendix A.

For each of the 41 lakeshore segments, Soltero et al. estimated the following key geometric and hydraulic properties:

- Length;
- Saturated thickness (assumed to extend from water surface to the average depth of the reservoir along that segment);
- Hydraulic conductivity (estimated by examination of grain-size distribution data for representative soil samples); and
- Mean hydraulic gradient (based on groundwater elevation data collected from project monitoring wells).

These data are used to estimate mean groundwater flux into and out of Lake Spokane from nearshore unconsolidated aquifers in Tables 1 and 2. Groundwater flux was estimated using a standard Darcy's Law-based analysis, as described in Equation 1:

$$Q = KA(dh/dl) \qquad \text{Equation 1}$$

where Q = groundwater flux;
K = hydraulic conductivity;
A = area of surface water/groundwater interface; and
dh/dl = hydraulic gradient at interface (assumed equivalent to mean gradients reported by Soltero et al.)

Estimated mean groundwater flux within lakeshore segments ranges from -2.9 cubic feet per second (cfs) in segment N10 to 4.3 cfs in segment N1. (Negative flux values represent flow out of Lake Spokane.) Groundwater flux values are summed to yield a mean baseflow estimate of 41.5 cfs for the entire lake. About 14.6 cfs of this baseflow enters the lake from the north margin and about 26.8 cfs enters from the south margin.

ASSUMED PHOSPHORUS CONCENTRATIONS IN GROUNDWATER

Soltero et al. (1992) reported total phosphorus and orthophosphate (soluble reactive phosphorus) concentrations for seven study areas of limited size adjacent to Lake Spokane, including the Little Sandy, Sunset Bay, Willow Bay, Suncrest, Cutler, Granger Road, and Tormey Road study areas. As such, groundwater phosphorus concentrations for the nearshore unconsolidated aquifers directly adjacent to many of the 41 lakeshore segments were not available. Based on hydrogeologic setting and surrounding land use conditions, GeoEngineers assigned a representative study area for each of the 41 lakeshore segments, as specified in Tables 1 and 2. Note that, because Soltero et al. likely selected study areas near suspected nutrient sources, this process may overestimate phosphorus concentrations for less disturbed portions of the lake.

Assumed total phosphorus (Table 1) and orthophosphate (Table 2) concentrations were assigned to each segment based on the mean total phosphorus and orthophosphate concentrations for the wells within the representative study areas, per examination of data reported by Soltero et al. (1992). Assumed total phosphorus concentrations ranged from 42 micrograms per liter (μg/l) to 324 μg/l and assumed orthophosphate concentrations ranged from 7 μg/l to 80 μg/l.

PRELIMINARY LOADING ANALYSIS

GeoEngineers used the above-described baseflow and phosphorus concentration estimates to estimate mean phosphorus loads entering Lake Spokane from nearshore unconsolidated aquifers. Loading estimates for total phosphorus and orthophosphate are provided in Tables 1 and 2, respectively, and were calculated using Equation 2:

$$L = QC \qquad \text{Equation 2}$$

where L = groundwater-based phosphorus load;
Q = baseflow; and
C = assumed phosphorus concentration.

Groundwater-based total phosphorus loads to Lake Spokane are summarized by lakeshore segment in Table 1 and ranged from 0.1 pounds per day (lbs/day) in segment N9 to 3.3 lbs/day in segment S1. Total phosphorus loads are summed to yield a mean loading estimate of 42.1 lbs/day for the entire lake. About 15.6 and 26.5 lbs/day of loading are estimated for the north and south margins of the reservoir, respectively.

Groundwater-based orthophosphate loads to Lake Spokane are summarized by lakeshore segment in Table 2 and ranged from 0.01 lbs/day in segments N9 and N21 to 3.3 lbs/day in segments N1, S1, and S14. Orthophosphate loads are summed to yield a mean loading estimate of 10.0 lbs/day for the entire lake. About 3.5 and 6.5 lbs/day of loading are estimated for the north and south margins of the reservoir, respectively.

Groundwater-based phosphorus loading directly to Lake Spokane is significant and could warrant additional investigation as this study or parallel studies proceed. This conclusion is based on the following considerations:

- The estimated total phosphorus load (42.1 lbs/day) is additional to the groundwater-based total phosphorus load estimated by GeoEngineers (2009) for the mainstem Spokane River, the Little Spokane River, and Hangman Creek, and represents over 26 percent of that previously estimated load.
- The estimated orthophosphate load (10.0 lbs/day) is additional to the groundwater-based orthophosphate load estimated by GeoEngineers (2010) for the mainstem Spokane River, the Little Spokane River, and Hangman Creek, and represents about 14 percent of that previously estimated load.
- There is no significant attenuation of this load before it reaches Lake Spokane, the portion of the watershed primarily impacted by low dissolved oxygen conditions.

Please contact us if you have any questions about the contents of this technical memorandum.

Sincerely,
GeoEngineers, Inc.

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Table 1

Total Phosphorus Loading to Lake Spokane From Nearshore Unconsolidated Aquifers

Groundwater Loading Analyses - Lake Spokane
Spokane, Washington

Lake Segment[1]	Length[2] (ft)	Saturated Thickness[2] (ft)	Area[3] (ft^2)	Hydraulic Conductivity[2] (ft/d)	Mean Hydraulic Gradient[2,4] ft/ft	Groundwater Flux[5] (cfs)	Representative Study Area[6]	Assumed Total Phosphorus Concentration[7] (µg/L)	Total Phosphorus Loading (lb/day)
N1	11,000	140	1,540,000	485	0.0005	4.3	Little Sandy	122	2.9
N2	6,000	120	720,000	485	0.0005	2.0	Little Sandy	122	1.3
N3	5,000	110	550,000	485	0.0005	1.5	Little Sandy	122	1.0
N4	3,500	110	385,000	485	0.0005	1.1	Little Sandy	122	0.7
N5	9,000	110	990,000	485	0.0005	2.8	Little Sandy	122	1.8
N6	5,000	100	500,000	485	0.0005	1.4	Little Sandy	122	0.9
N7	2,000	90	180,000	485	0.0005	0.5	Little Sandy	122	0.3
N8	3,500	80	280,000	230	0.0006	0.4	Little Sandy	122	0.3
N9	2,500	80	200,000	230	0.0006	0.3	Sunset Bay	42	0.07
N10	3,500	70	245,000	230	-0.0045	-2.9	Sunset Bay		
N11	4,000	70	280,000	230	0.0006	0.4	Willow Bay	224	0.5
N12	2,500	70	175,000	485	0.0005	0.5	Little Sandy	122	0.3
N13	4,000	70	280,000	485	0.0005	0.8	Little Sandy	122	0.5
N14	8,000	60	480,000	485	0.0005	1.3	Little Sandy	122	0.9
N15	2,500	60	150,000	485	0.0005	0.4	Little Sandy	122	0.3
N16	2,000	50	100,000	400	-0.0020	-0.9	Little Sandy		
N17	4,000	40	160,000	400	-0.0020	-1.5	Little Sandy		
N18	10,000	40	400,000	485	0.0005	1.1	Suncrest	324	2.0
N19	5,000	30	150,000	485	0.0005	0.4	Suncrest	324	0.7
N20	7,000	20	140,000	485	0.0005	0.4	Suncrest	324	0.7
N21	2,500	20	50,000	485	0.0005	0.1	Suncrest	324	0.2
S1	8,500	140	1,190,000	485	0.0005	3.3	Cutler	183	3.3
S2	4,500	130	585,000	485	0.0005	1.6	Cutler	183	1.6
S3	7,000	120	840,000	485	0.0005	2.4	Cutler	183	2.3
S4	3,500	110	385,000	485	0.0005	1.1	Cutler	183	1.1
S5	9,000	110	990,000	485	0.0005	2.8	Cutler	183	2.7
S6	3,500	110	385,000	485	0.0005	1.1	Cutler	183	1.1
S7	2,000	100	200,000	485	0.0005	0.6	Cutler	183	0.6
S8	2,500	90	225,000	485	0.0005	0.6	Cutler	183	0.6
S9	4,500	90	405,000	485	0.0005	1.1	Cutler	183	1.1

Lake Segment[1]	Length[2] (ft)	Saturated Thickness[2] (ft)	Area[3] (ft^2)	Hydraulic Conductivity[2] (ft/d)	Mean Hydraulic Gradient[2,4] ft/ft	Groundwater Flux[5] (cfs)	Representative Study Area[6]	Assumed Total Phosphorus Concentration[7] (µg/L)	Total Phosphorus Loading (lb/day)
S10	7,000	80	560,000	485	0.0005	1.6	Cutler	183	1.6
S11	2,500	80	200,000	485	0.0005	0.6	Cutler	183	0.6
S12	6,000	70	420,000	485	0.0005	1.2	Cutler	183	1.2
S13	9,000	70	630,000	485	0.0005	1.8	Cutler	183	1.7
S14	5,000	60	300,000	2370	0.0004	3.3	Cutler	183	3.2
S15	5,500	40	220,000	2370	0.0004	2.4	Cutler	183	2.4
S16	4,500	30	135,000	485	0.0005	0.4	Cutler	183	0.4
S17	7,000	30	210,000	485	0.0005	0.6	Cutler	183	0.6
S18	3,500	30	105,000	230	0.0006	0.2	Granger	211	0.2
S19	5,500	20	110,000	230	0.0006	0.2	Granger	211	0.2
S20	4,000	20	80,000	230	0.0006	0.1	Granger	211	0.1
						41.5			**42.1**

Notes:

[1]Lake segment refers to the Lake Spokane shoreline segment definitions introduced by Soltero et. al. (1992) for the purpose of estimating baseflow.

[2]The lake segment length, as well as the thickness, hydraulic conductivity, and mean hydraulic gradient associated with the groundwater/surface water interface, was derived from Soltero et al. (1992).

[3]Area of the groundwater/surface water interface is the product of saturated thickness and length associated with the individual lake segment.

[4]A negative hydraulic gradient refers to losing conditions within Lake Spokane.

[5]Groundwater flux refers to the rate of water movement through the groundwater/surface water interface and was calculated using Darcy's Law.

[6]Representative study area refers to the aquifer study site from Soltero et. al. (1992) that best correlates with the hydrogeologic and land use setting associated with the individual lake segment.

[7]The assumed phosphorus concentration is the mean total phosphorus concentration for the wells within the representative study area, from Soltero et. al. (1992).

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Table 2

Orthophosphate Loading to Lake Spokane From Nearshore Unconsolidated Aquifers

Groundwater Loading Analyses - Lake Spokane
Spokane, Washington

Lake Segment[1]	Length[2] (ft)	Saturated Thickness[2] (ft)	Area[3] (ft^2)	Hydraulic Conductivity[2] (ft/d)	Mean Hydraulic Gradient[2,4] ft/ft	Groundwater Flux[5] (cfs)	Representative Study Area[6]	Assumed Orthophosphate Concentration[7] (µg/L)	Total Orthophosphate Loading (lb/day)
N1	11,000	140	1,540,000	485	0.0005	4.3	Little Sandy	34	0.8
N2	6,000	120	720,000	485	0.0005	2.0	Little Sandy	34	0.4
N3	5,000	110	550,000	485	0.0005	1.5	Little Sandy	34	0.3
N4	3,500	110	385,000	485	0.0005	1.1	Little Sandy	34	0.2
N5	9,000	110	990,000	485	0.0005	2.8	Little Sandy	34	0.5
N6	5,000	100	500,000	485	0.0005	1.4	Little Sandy	34	0.3
N7	2,000	90	180,000	485	0.0005	0.5	Little Sandy	34	0.09
N8	3,500	80	280,000	230	0.0006	0.4	Little Sandy	34	0.08
N9	2,500	80	200,000	230	0.0006	0.3	Sunset Bay	7	0.01
N10	3,500	70	245,000	230	-0.0045	-2.9	Sunset Bay		
N11	4,000	70	280,000	230	0.0006	0.4	Willow Bay	80	0.2
N12	2,500	70	175,000	485	0.0005	0.5	Little Sandy	34	0.09
N13	4,000	70	280,000	485	0.0005	0.8	Little Sandy	34	0.1
N14	8,000	60	480,000	485	0.0005	1.3	Little Sandy	34	0.2
N15	2,500	60	150,000	485	0.0005	0.4	Little Sandy	34	0.08
N16	2,000	50	100,000	400	-0.0020	-0.9	Little Sandy		
N17	4,000	40	160,000	400	-0.0020	-1.5	Little Sandy		
N18	10,000	40	400,000	485	0.0005	1.1	Suncrest	12	0.07
N19	5,000	30	150,000	485	0.0005	0.4	Suncrest	12	0.03
N20	7,000	20	140,000	485	0.0005	0.4	Suncrest	12	0.03
N21	2,500	20	50,000	485	0.0005	0.1	Suncrest	12	0.01
S1	8,500	140	1,190,000	485	0.0005	3.3	Cutler	45	0.8
S2	4,500	130	585,000	485	0.0005	1.6	Cutler	45	0.4
S3	7,000	120	840,000	485	0.0005	2.4	Cutler	45	0.6
S4	3,500	110	385,000	485	0.0005	1.1	Cutler	45	0.3
S5	9,000	110	990,000	485	0.0005	2.8	Cutler	45	0.7
S6	3,500	110	385,000	485	0.0005	1.1	Cutler	45	0.3
S7	2,000	100	200,000	485	0.0005	0.6	Cutler	45	0.1
S8	2,500	90	225,000	485	0.0005	0.6	Cutler	45	0.2
S9	4,500	90	405,000	485	0.0005	1.1	Cutler	45	0.3
S10	7,000	80	560,000	485	0.0005	1.6	Cutler	45	0.4

Lake Segment[1]	Length[2] (ft)	Saturated Thickness[2] (ft)	Area[3] (ft^2)	Hydraulic Conductivity[2] (ft/d)	Mean Hydraulic Gradient[2,4] ft/ft	Groundwater Flux[5] (cfs)	Representative Study Area[6]	Assumed Orthophosphate Concentration[7] (µg/L)	Total Orthophosphate Loading (lb/day)
S11	2,500	80	200,000	485	0.0005	0.6	Cutler	45	0.14
S12	6,000	70	420,000	485	0.0005	1.2	Cutler	45	0.3
S13	9,000	70	630,000	485	0.0005	1.8	Cutler	45	0.4
S14	5,000	60	300,000	2370	0.0004	3.3	Cutler	45	0.8
S15	5,500	40	220,000	2370	0.0004	2.4	Cutler	45	0.6
S16	4,500	30	135,000	485	0.0005	0.4	Cutler	45	0.09
S17	7,000	30	210,000	485	0.0005	0.6	Cutler	45	0.1
S18	3,500	30	105,000	230	0.0006	0.2	Granger	31	0.03
S19	5,500	20	110,000	230	0.0006	0.2	Granger	31	0.03
S20	4,000	20	80,000	230	0.0006	0.1	Granger	31	0.02
						41.5			**10.0**

Notes:

[1]Lake segment refers to the Lake Spokane shoreline segment definitions introduced by Soltero et. al. (1992) for the purpose of estimating baseflow.

[2]The lake segment length, as well as the thickness, hydraulic conductivity, and mean hydraulic gradient associated with the groundwater/surface water interface, was derived from Soltero et al. (1992).

[3]Area of the groundwater/surface water interface is the product of saturated thickness and length associated with the individual lake segment.

[4]A negative hydraulic gradient refers to losing conditions within Lake Spokane.

[5]Groundwater flux refers to the rate of water movement through the groundwater/surface water interface and was calculated using Darcy's Law.

[6]Representative study area refers to the aquifer study site from Soltero et. al. (1992) that best correlates with the hydrogeologic and land use setting associated with the individual lake segment.

[7]The assumed orthophosphate concentration is the mean soluble reactive phosphorus concentration for the wells within the representative study area, from Soltero et. al. (1992).

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APPENDIX A
Lakeshore Segment Locations

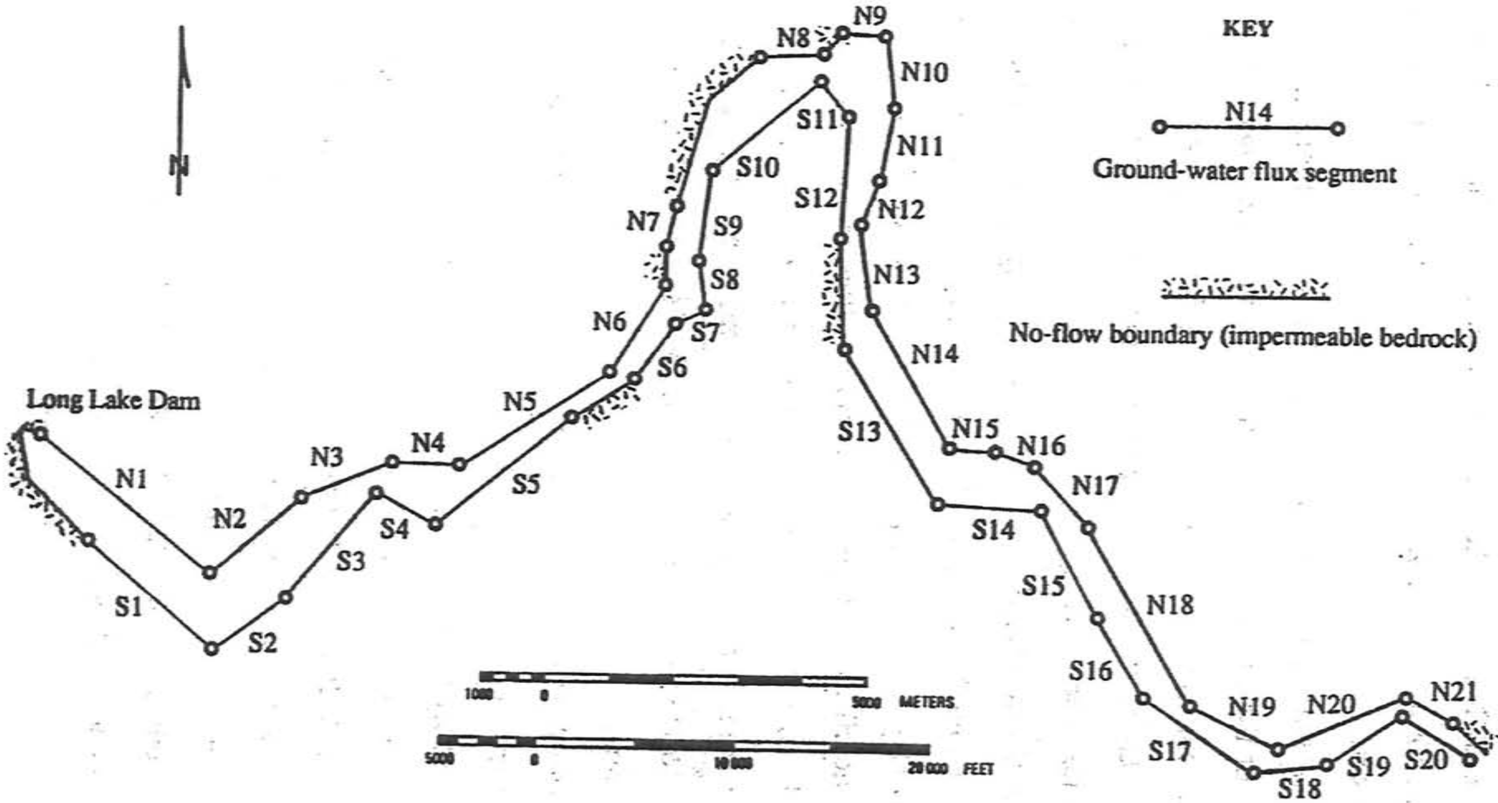

Figure 35. Schematic illustration of the groundwater flow model developed for the Long Lake, WA hydrogeologic system showing numbered groundwater flux segments and assumed no-flow boundaries.

APPENDIX B
References

APPENDIX B
REFERENCES

GeoEngineers, Inc., 2009, Preliminary Groundwater Loading Analyses, Bi-State Nonpoint Source Phosphorus Study. Prepared by GeoEngineers, Inc., Spokane, Washington for Spokane County Department of Utilities, Spokane, Washington, August 4.

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