Oklahoma Water Resources Board

Lake Thunderbird Hydraulic and Nutrient Budget 2005

for the

Central Oklahoma Master Conservancy District

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Final Report

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Hydraulic Budget

A hydrologic or water balance is of considerable importance in water quality analyses and management. A general and simple hydrologic budget equation for a given water body such as a lake is given by

$$dV/dt = Q_{in} - Q + PA_s - E_vA_s - W_S$$

where V = lake volume [L^3],

A_s = lake surface area [L^2],

Q_{in} and Q [L^3/T] represent net flows into and out of the lake due to tributary inflows and gated releases,

P [L/T] is the precipitation directly on the lake,

E_v [L/T] is the lake evaporation,

W_S is the water exported for water supply use.

In other words, the rate of change in storage of the volume of water in or on the given area per unit time is equal to the rate of inflow from all sources minus the rate of outflows.

The input or inflows to a lake may include surface inflow, subsurface inflow, and water imported into the lake. The outputs may include surface and subsurface outputs and water exported (e.g. water supply) from the lake. For Lake Thunderbird we will assume that subsurface flow is insignificant, based on the relatively impermeable lake substrate.

The inputs to Lake Thunderbird are precipitation or rainfall and inflow from the tributaries, which includes all surface runoff in the basin. The outputs are evaporation, dam releases (spilled), and water supply.

Precipitation (directly on the lake surface)

Precipitation was estimated from the direct rainfall measurements/data provided by the USACE. The precipitation contribution to the total inflows was obtained by multiplying the daily rainfall amounts by the surface area of the lake on each date, as shown in equation 2.

$$Q_P = P*A_s$$

where P [L/T] is rainfall amount and A_s [L^2] is the surface area of the lake.

Evaporation

Daily evaporation rates were calculated and reported by the USACE. Empirical equations were used to relate solar radiation, wind speed, relative humidity, and average daily air temperature to the rate of evaporation from the lake. These rates are multiplied by the annual average surface area of the lake to give the amount of water evaporated per unit time.

$$\mathbf{Q_E = E_v * A_s}$$

where E_v [L/T] is the evaporation rate and A_s [L^2] is the surface area of the lake.

Water Releases

Water released from Lake Thunderbird includes gated dam releases and water supply releases. Both are reported by the USACE.

Change in Lake Volume

Change in volume or storage was recorded by the USACE at the end of every day. The lake volumes corresponding to the stages were computed and the difference between them is the change in volume for that month. The volumes were estimated from elevation-capacity curves generated from the OWRB's 2001 bathymetric survey of the lake.

Results

A summary of the water budget calculations on a monthly basis for Lake Thunderbird, using inflows generated by the USACE, is presented in **Table 1**. Total input is the sum of all the flows into the lake. Total output is the sum of all the outflows from the lake. From equation 1, the difference between the inputs and the outputs must be the same as the change in volume of the lake for an error free water budget. The difference between the inflow and outflow is in the I-O column of **Table 1**. Total error is calculated as the difference between the change in lake volume and I-O. Examination of the estimated budget for lake Thunderbird shows that estimated inputs and outputs are close to the actual volume changes with relatively little error.

Table 1: 2005 Budget Summary for Lake Thunderbird, units in acre-feet.

Month	INPUTS			OUTPUTS				RESULTS		
	Inflow	Rainfall	Total inputs	Evaporation	Water supply	Releases	Total outputs	I-O	ΔV	Error
Jan	6,724	1,021	7,745	1,252	1,264	0	2,516	5,229	3,807	1,422
Feb	6,060	913	6,972	1,656	1,073	7,008	9,737	-2,765	-2,470	-295
Mar	3,005	485	3,490	2,605	1,269	123	3,997	-506	-669	163
Apr	2,212	96	2,307	3,449	1,499	0	4,948	-2,640	-1,646	-994
May	2,370	820	3,191	3,471	1,838	0	5,309	-2,119	-1,852	-267
Jun	5,167	1,704	6,871	4,625	1,765	0	6,390	481	-360	841
Jul	3,475	2,021	5,496	5,514	1,928	0	7,442	-1,945	-2,212	267
Aug	5,230	1,444	6,675	4,171	1,939	0	6,110	565	0	565
Sep	1,160	761	1,921	3,892	1,838	0	5,730	-3,809	-3,499	-310
Oct	813	1,201	2,014	2,817	1,601	0	4,418	-2,404	-2,521	117
Nov	2	0	2	2,296	1,276	0	3,572	-3,570	-3,447	-123
Dec	61	98	159	1,164	1,220	0	2,384	-2,225	-1,955	-270
Total	36,279	10,564	46,843	36,912	18,510	7,131	62,552	-15,709	-16,824	1,115

Once a hydraulic budget has been constructed, retention times can be estimated. The hydraulic detention time is the ratio of lake capacity at normal pool elevation to the exiting flow (usually on an annual basis). This represents the theoretical time it would take a given molecule of water to flow through the reservoir. The combination of lake releases and water supply withdrawals give Lake Thunderbird water a hydraulic residence time of 2.17 years, averaged over the 11-year record of lake levels, and 3.98 years for 2005. The longer residence time reflects drought conditions experienced in 2005. This is further evidenced when comparing the total inputs (46,843 acre-feet) verses total outputs (62,552 acre-feet) representing a dropping annual pool. Finally only in January, June and August were inputs predicted to be greater than outputs (gaining pool months) (**Figure 1**).

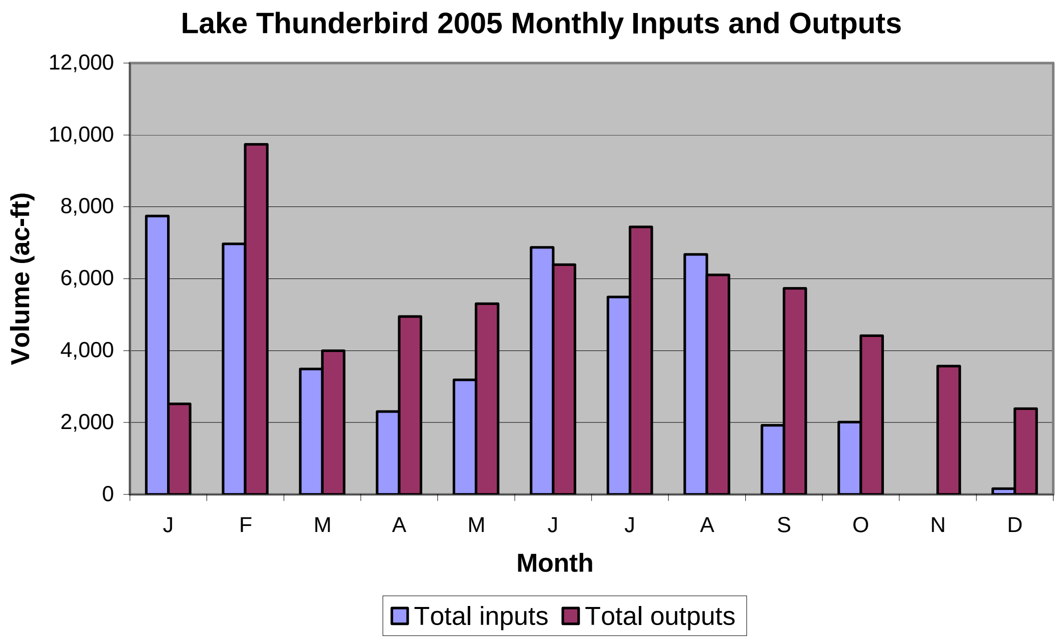
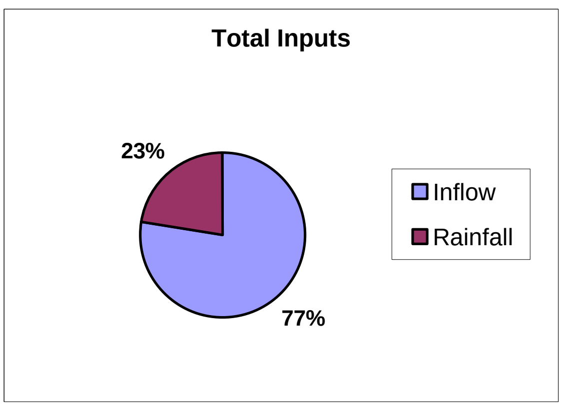


Figure 1: **Total inflows to the lake compared with total outflows for Lake Thunderbird, 2005.**

During this last drought year, 77% of the input to Lake Thunderbird was from inflow while evaporation accounted for 59% of the water lost from the lake with only 11% of the total spilled below the dam (**Figure 2**). During non-drought years a larger portion of input would be expected from runoff with a greater proportion amount of loss from spillage.



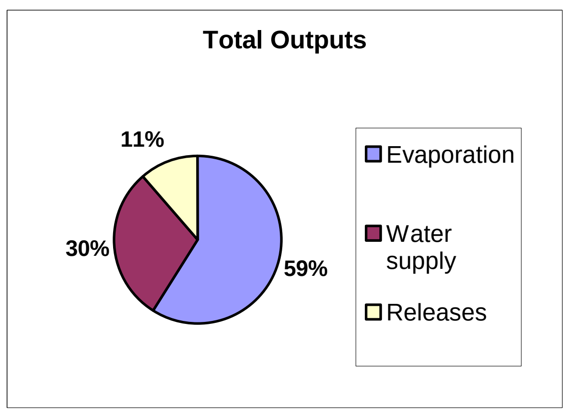


Figure 2: Summary of inflow and outflow sources as percent of the total.

Sources of Error

Although robust, the hydraulic budget does contain error. For example of the three months with greater inflow than outflow (Jan., June and Aug.), only in January was a gaining pool elevation recorded. Although seemingly significant, the magnitude of error is less than 2% of the lake capacity suggests the error is nominal and heightened by drought conditions. Based on the simplifying assumptions made in calculating some of the parameters, the following potential sources of error have been identified.

- Evaporation rates used in the calculation of water losses due to evaporation were calculated rather than measured.

- Groundwater loss and gain to the lake were assumed to be negligible. This should be verified with field measurements or through a review of the geology in the area.

- Transpiration through plants and seepage through the dam were assumed to be negligible.

- Inflow from the tributaries was estimated by the USACE based on changes in lake volume using the original lake bathymetry. The 2001 survey showed significant sedimentation of the lake, which could greatly change the calculation of inflows.

Of these potential sources of error the greatest source of uncertainty in the budget is inflow. Implementing two of three actions would reduce uncertainty of inflow estimates: install a gauge and record instantaneous flow on the main tributary to the lake, develop modeled estimates of inflow to the lake, and back calculate inflow volume based on recent bathymetry. It is important to note that the hydraulic budget is robust enough to support lake nutrient budget development.

Nutrient Budget

A phosphorus budget for Lake Thunderbird was prepared integrating the estimated outflows from the water budget with the lake water quality data. The constructed budget shows baseline lake phosphorus mass near 3,750 kg (**Table 2**). The lowest (3,307 kg) and highest (6,804 kg) amounts of lake total phosphorus were July and August respectively. Enhancements to increase the accuracy of the nutrient budget include assessing dry deposition and estimates of inflow load. This preliminary budget has set the foundation for understanding lake nutrient dynamics and placing external (runoff) and internal (sediment mediated release) in context of water quality based goals. Additional work to better understand nutrient dynamics would be to construct a nitrogen budget.

Lake monitored data was used for internal inputs and outputs of phosphorus. Lake water quality data was collected by the OWRB for the purpose of nutrient budgeting in fiscal year 2006 (June 2005 to June 2006). Vertical profiles of physical parameters were used to establish internal reservoir dynamics. Partitioning between epilimnetic, metalimnetic and hypolimnetic layers allowed the massing of phosphorus. To complete the massing of Lake Thunderbird phosphorus sample dates were grouped to yield monthly amounts. Once the lake mass was established the distribution within the lake and losses were estimated using COE water quantity reports and OWRB water quality reports. Missing from this lake nutrient budget are estimates of inflow and dry deposition. Experience shows that dry deposition of phosphorus is nominal while inflow loads are significant.

The distribution of phosphorus as total and dissolved ortho-phosphrus were estimated from the dataset to represent the proportion of phosphorus immediately available for plant growth and to indicate accumulation of phosphorus in the hypolimnion. During mixed or oxidized lake conditions, ortho-phosphorus represents approximately one-quarter the total phosphorus in the lake while this proportion doubles from August through October (**Table 2**). This proportional increase corresponds to an accumulation of phosphorus in the hypolimnion (**Table 3**). Three possibilities exist for the hypolimnetic accumulation of ortho-phosphorus: accumulation of dying algae (settling) from the epilimnion, release from the sediment, and plunging runoff from the watershed. Partitioning between these three sources require more accurate estimates of inflow load. Until water quality data is available for the tributaries to the lake, the total mass of phosphorus from inflow cannot be established.

Table 2: Partitioning of phosphorus mass for nutrient budget as total phosphorus (TP) and ortho-phosphorus (OP).

Month	Lake kg TP	Lake kg OP	Releases kg TP	Releases kg OP	Water supply kg TP	Water supply kg OP
January			0	0	42	11
February	3594	932	233	61	36	9
March			4	1	42	11
April			0	0	50	13
May	3325	772	0	0	57	14
June	3963	1450	0	0	54	13
July	3307	791	0	0	62	14
August	6804	3426	0	0	60	13
September	5354	2165	0	0	67	14
October	4671	1340	0	0	79	24
November			0	0	63	19
December			0	0	60	18

Although inconclusive it is notable that the hypolimnetic accumulation of ortho and total phosphorus coincides with anoxic conditions. Comparison of ortho-phosphorus to total phosphorus by depth shows the bulk of the accumulation is as ortho-phosphorus (**Table 4**). The large proportion of ortho-phosphorus indicates sediment mediated release could be a significant contributor to the net gain of Lake Thunderbird phosphorus mass in 2005.

Table 3: Total Phosphorus mass (kg) by lake layer for each sample date. Hypolimnetic accumulation of phosphorus is noted in red.

Depth (m)	2/28	5/24	6/21	7/21	8/18	9/15	9/27	10/13
0-1	502	515	517	509	579	537	570	722
1-2	458	457	457	447	508	471	500	633
2-3	407	390	393	391	446	414	440	557
3-4	364	350	352	360	381	366	388	491
4-5	326	308	309	316	334	320	375	465
5-6	290	268	269	275	290	279	326	404
6-7	257	232	233	237	249	239	279	346
7-8	226	195	401	200	218	209	235	305
8-9	192	163	334	166	180	173	187	250
9-10	163	171	267	131	1410	133	143	189
10-11	135	119	186	112	966	1542	97	137
11-12	102	77	120	71	612	975	173	86
12-13	72	45	71	42	347	550	96	47
13-14	48	21	33	19	162	257	45	26
14-15	29	10	15	21	89	134	155	11
15-16	14	3	6	8	30	44	40	3
16-16.5	10	0	1	1	1	5	13	0
16.5+		0		0	2			
Total	3594	3325	3963	3307	6804	6646	4061	4671

Table 4: Ortho Phosphorus (kg) by lake layer for each sample date. Hypolimnetic accumulation of ortho-phosphorus is noted in red.

Depth (m)	2/28	5/24	6/21	7/21	8/18	9/15	9/27	10/13
0-1	130	124	124	122	100	119	98	156
1-2	119	110	110	107	88	105	86	137
2-3	105	94	94	94	77	92	76	120
3-4	94	84	84	83	82	81	67	106
4-5	84	74	74	73	71	71	70	140
5-6	75	64	65	64	62	62	61	121
6-7	67	56	56	55	53	53	52	104
7-8	58	47	236	46	38	45	44	131
8-9	50	39	197	38	31	37	30	107
9-10	42	31	157	30	1098	28	23	81
10-11	35	22	109	28	752	1217	16	61
11-12	27	14	70	18	477	770	53	38
12-13	19	8	42	10	271	434	29	21
13-14	12	4	20	5	126	203	14	11
14-15	7	2	9	12	73	111	106	5
15-16	4	1	3	4	24	36	28	1
16-16.5	3	0	0	0	1	4	9	0
16.5+		0		0	2			
Total	932	772	1450	791	3426	3469	862	1340