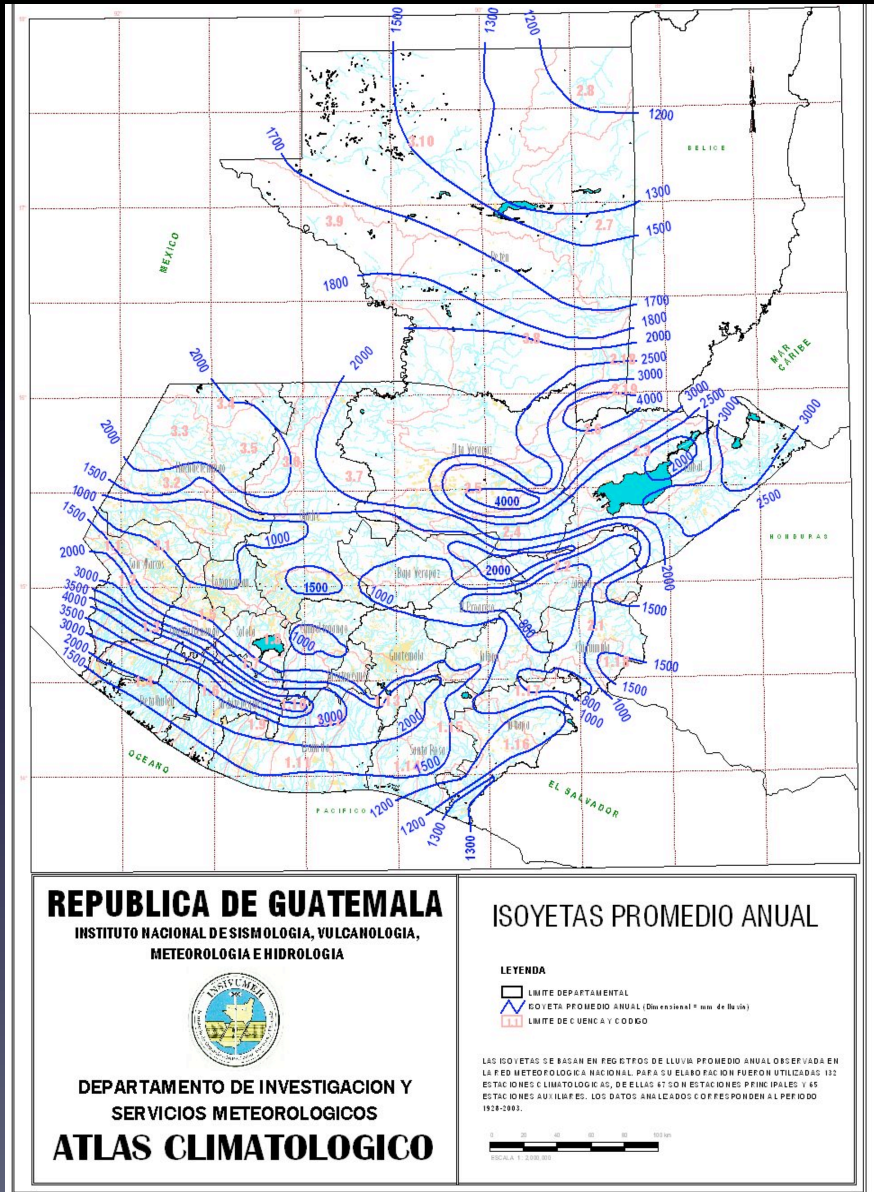
A Hydrologic Model for Water Level in the Maya Reservoirs of Central Tikal

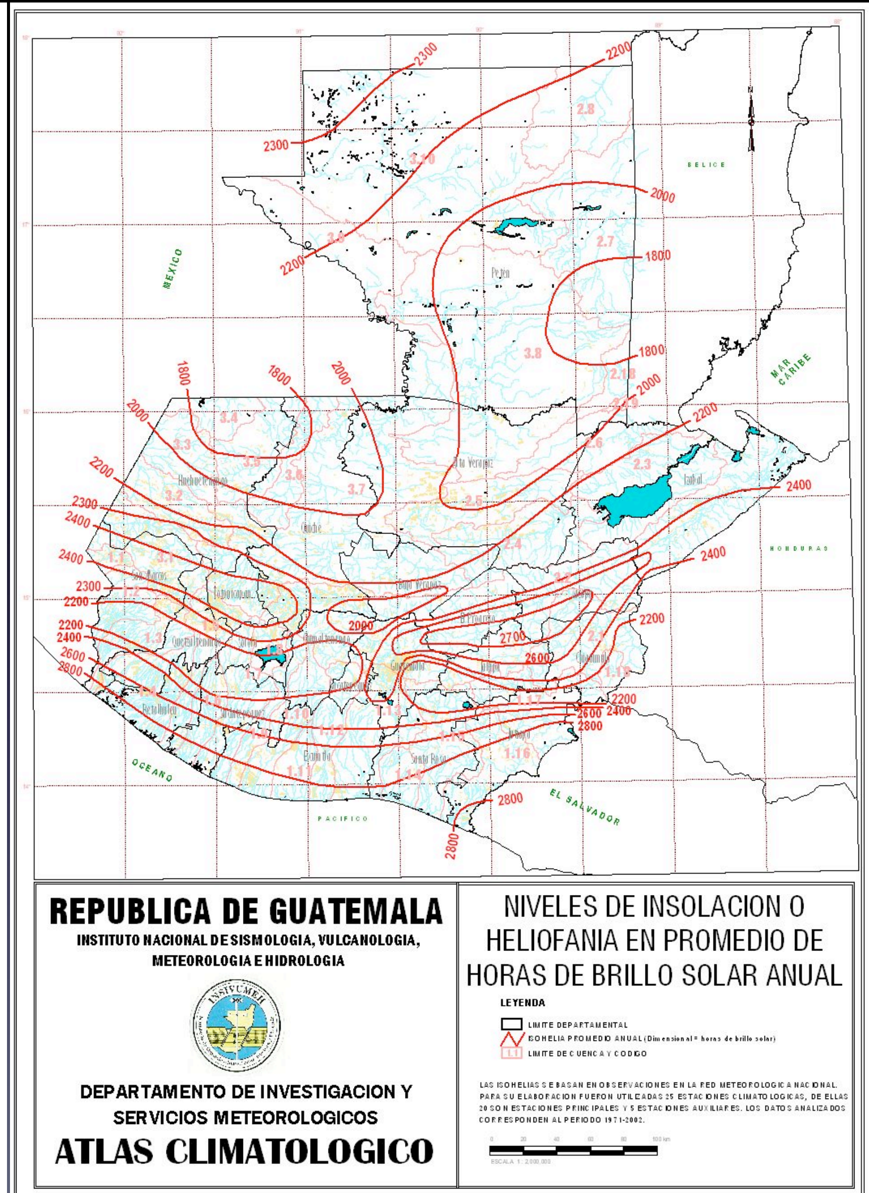
Lee Florea & Eric Weaver

GSA 2012 – Florea - Location

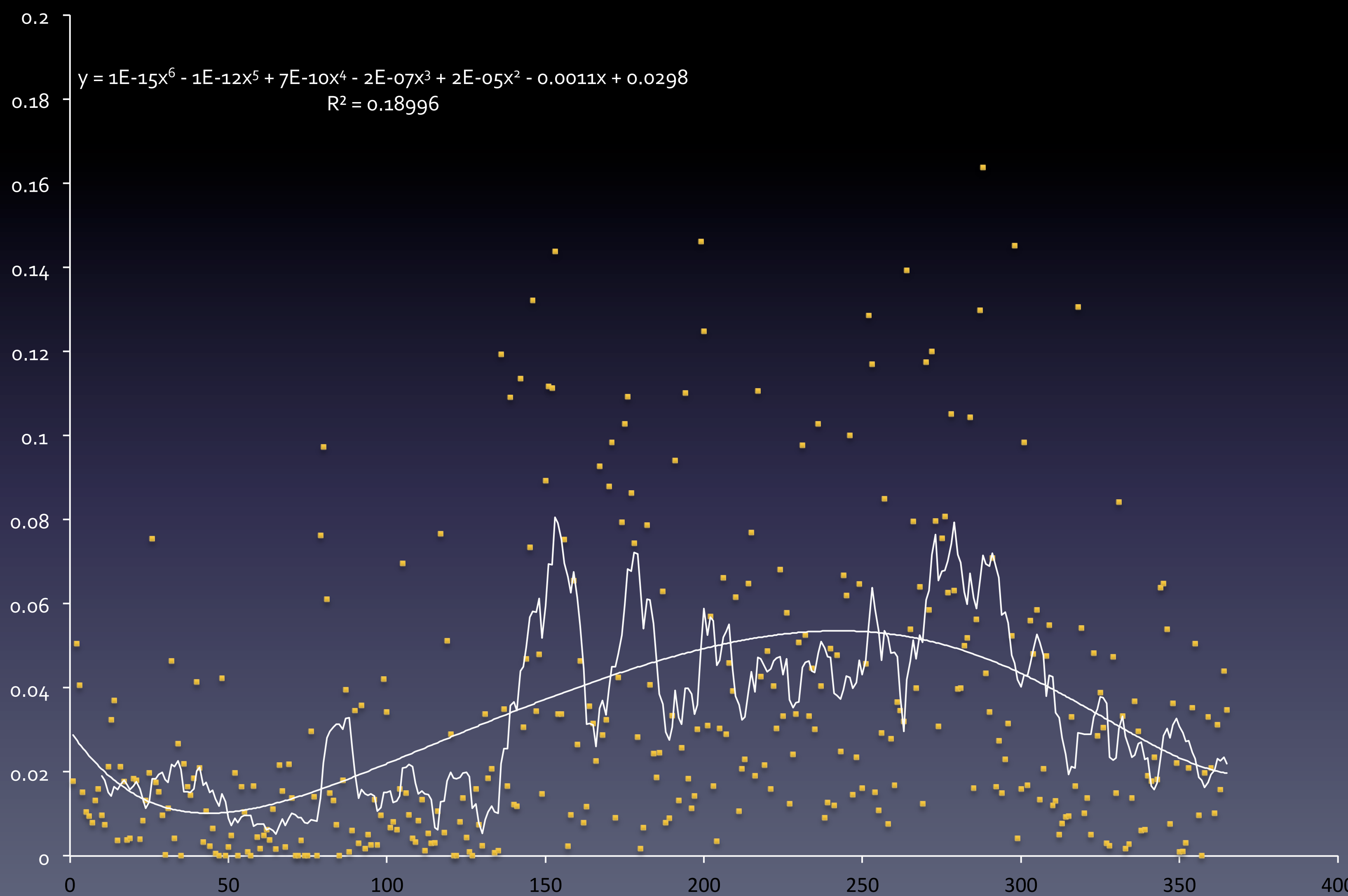
The Peten comprises a series of near-horizontal Cretaceous limestone, largely breccia. These limestone strata dip slightly into the Peten Basin. To the north and the south of Tikal are ranges of hills that mark the southern margin of basinward dipping strata, or faults, or both. Elevations range between 200 and 300 m with a water table that is at least 100 m below the surface. Surface waters are present to the south at a series of lakes, including Lake Peten Itza.

GSA 2012 – Florea - Climate

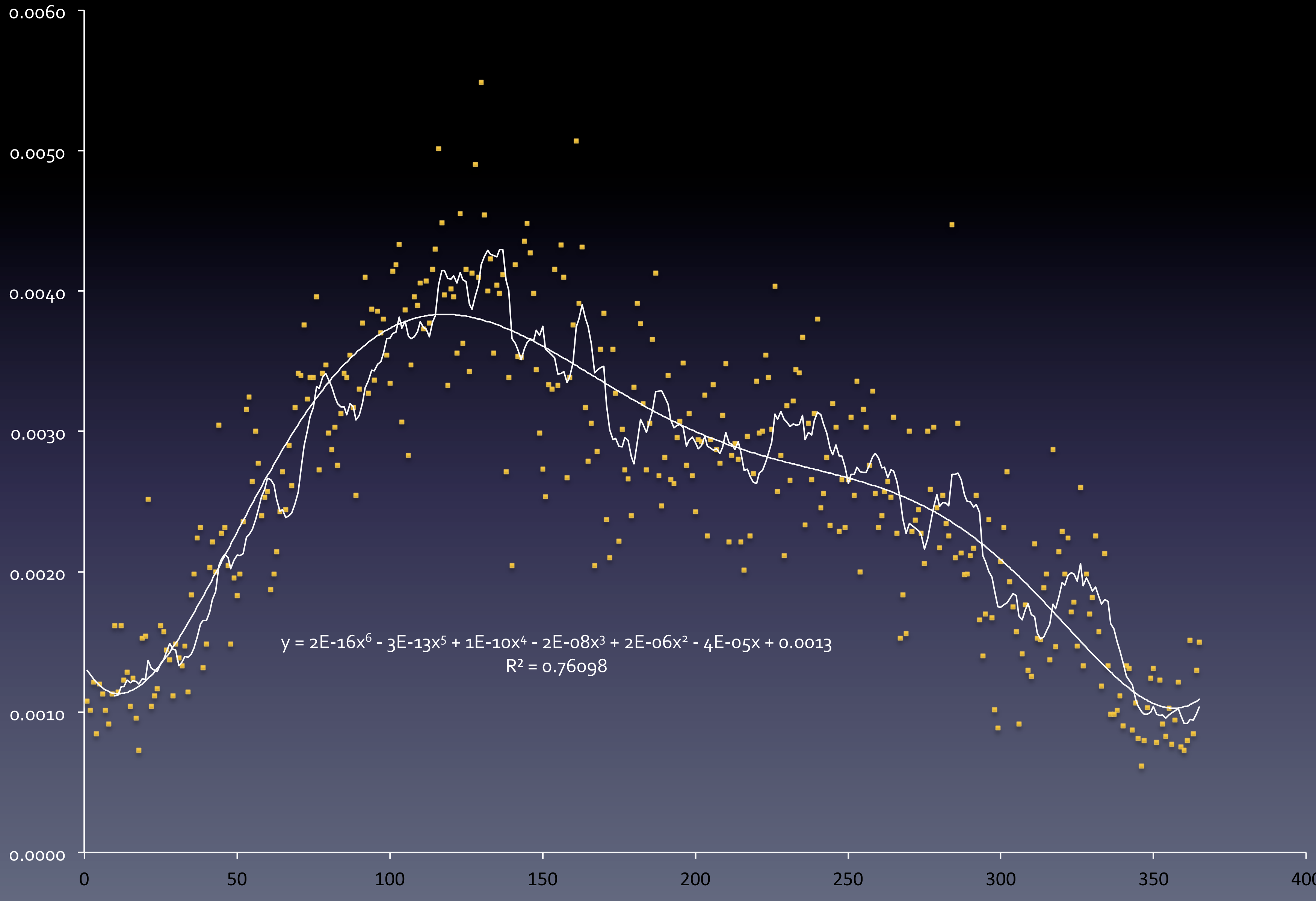




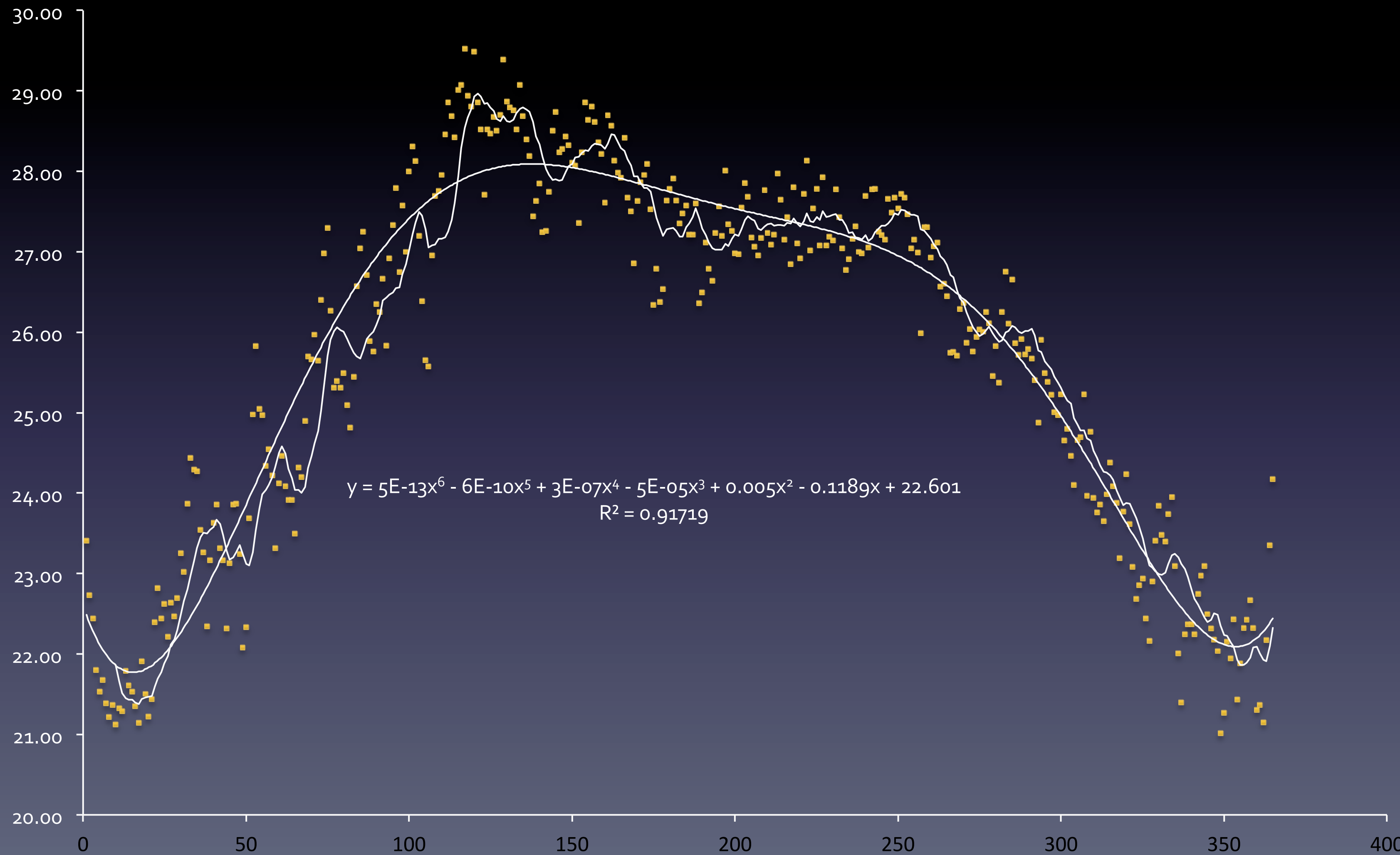
GSA 2012 – Florea –Tikal Precipitation 2001—2010



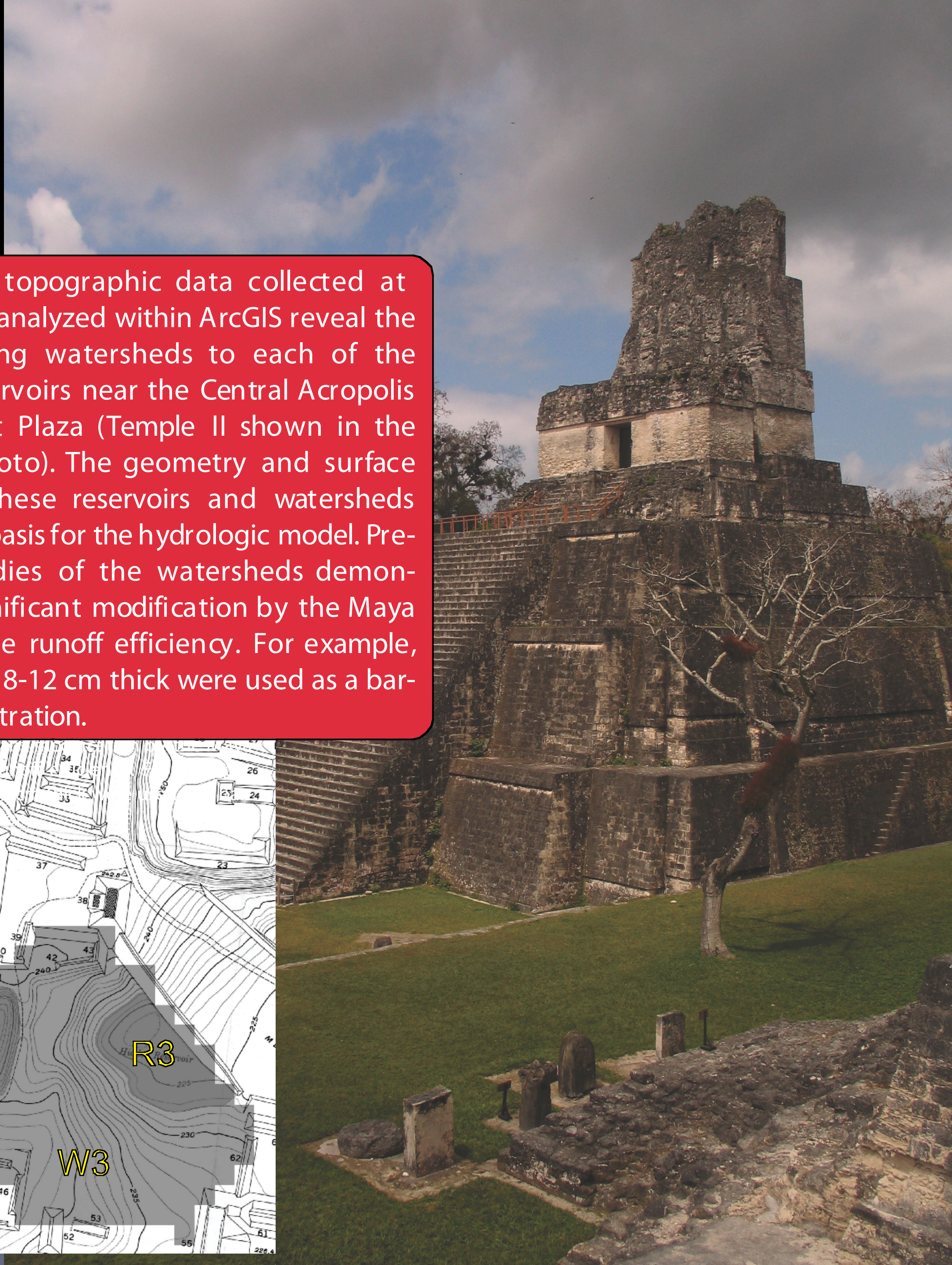
GSA 2012 – Florea –Tikal Evaporation 2001—2010



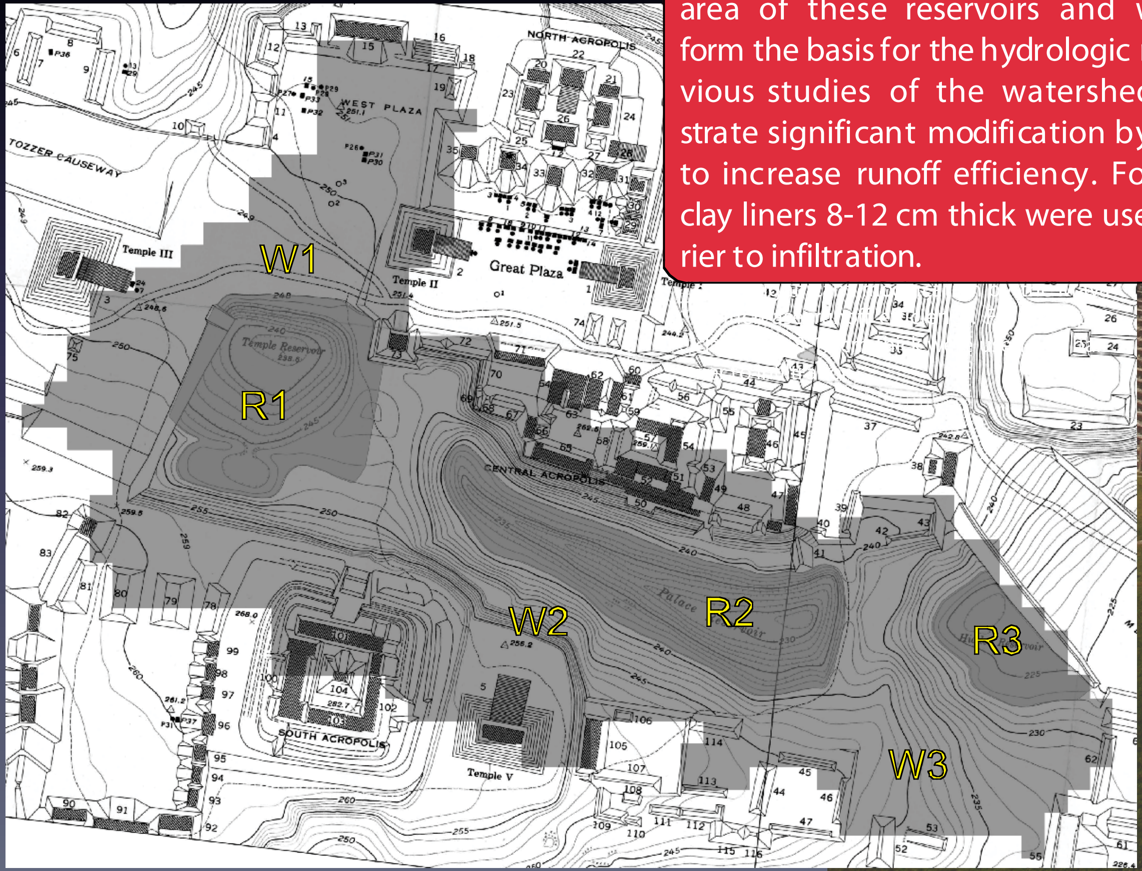
GSA 2012 – Florea –Tikal Temperature 2001—2010



GSA 2012 – Florea - Reservoirs

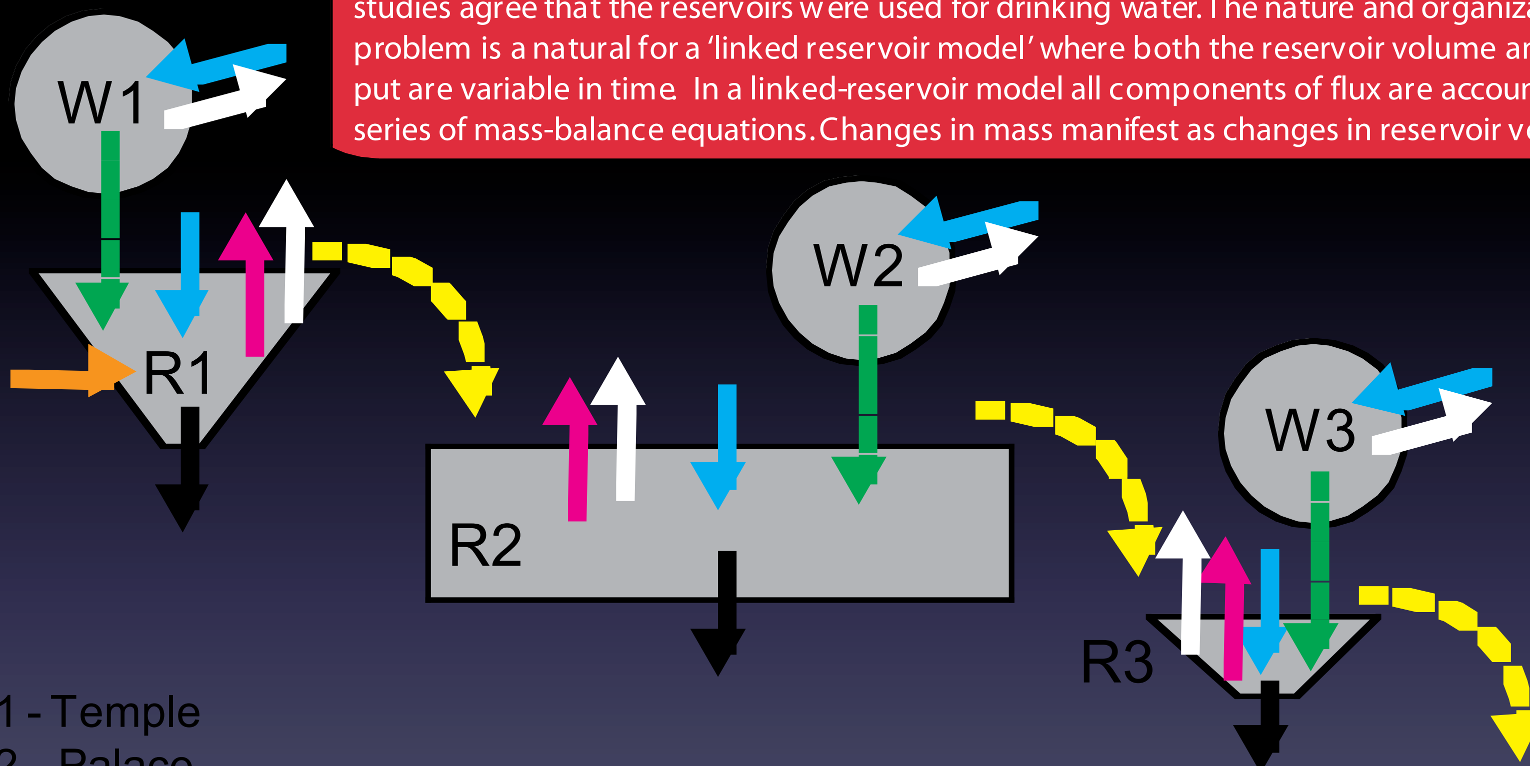


Detailed topographic data collected at Tikal and analyzed within ArcGIS reveal the contributing watersheds to each of the three reservoirs near the Central Acropolis and Great Plaza (Temple II shown in the above photo). The geometry and surface area of these reservoirs and watersheds form the basis for the hydrologic model. Previous studies of the watersheds demonstrate significant modification by the Maya to increase runoff efficiency. For example, clay liners 8-12 cm thick were used as a barrier to infiltration.



GSA 2012 – Florea – Conceptual Model

The three reservoirs are separated by clay-lined earthen dams. Previous investigations by archaeologists alternatively suggest that the reservoirs served as permanent lakes or hydrated wetlands. At least one investigation noted groundwater flow into the Temple Reservoir. Some studies indicate that overflow from the central reservoirs complemented irrigation needs. All studies agree that the reservoirs were used for drinking water. The nature and organization of this problem is a natural for a 'linked reservoir model' where both the reservoir volume and through-put are variable in time. In a linked-reservoir model all components of flux are accounted for in a series of mass-balance equations. Changes in mass manifest as changes in reservoir volume.



1 - Temple
2 - Palace
3 - Hidden

Blue - Precipitation
White - Evapotranspiration
Green - Overland Flow
Yellow - Overflow
Red - Pumping
Black - Seepage
Orange - Groudwater recharge

GSA 2012 – Florea – Model Design

Temple Reservoir			Palace Reservoir			Hidden reservoir		
Shape = cone			Shape = depening wedge			Shape = half cone		
Runoff efficiency	0.46	%	Rth	0.46	%	Rth	0.46	%
Liner Thickness	0.1	m	b	0.1	m	b	0.1	m
Hydro Conductivity	0.00000001	m/s	K	0.00000001	m/s	K	0.00000001	m/s
Surface area @ max D	11,520	m^2	SA @ max D	12,721	m^2	SA @ max D	3,780	m^2
Max reservoir D	9.4	m	Av Max R D	10	m	Max R D	4	m
Watershed area	41,294	m^2	W	46,454	m^2	W	25,462	m^2
Average slope	8.82	degrees	m	20.67	degrees	m	4.66	degrees

T = Daily average temperature, I = Average daily solar insolation, P = Daily precipitation, H = reservoir depth, SA =reservoir surface area, WP = reservoir wetted perimeter, alpha = Penman's alpha, rho = water density, HL= Latent heat of fusion, E = Daily evaporation, L= Leakage, L' = Specific leakage, Q = Pumping rate, Q' = Specific pump rate, R = Surface recharge, R' = Specific rechage, dH = Change in reservoir height.

***Surface Area is limited to greater than 100 m^2 to prevent model instability.**
***K values are adapted from a layered clay (Bear, 1972)**
***Starting depth is given as blue shaded area in PNAS 2012 article, potential overflow in Temple Reservoir is directed to recharge in Palace Reservoir**
***Runoff is given by daily precip - Evap * Efficiency (Li et al., 2004) *Temple Reservoir has additional spring input of 7.5 l/hr (PNAS 2012)**

Number of dependants	Liters per dependant per day
1200	4.000

DAY	Climate Data T (C)	E (m)	P (m)	Temple Reservoir H (m)	SA (m^2)	WP (m^2)	Palace Reservoir H (m)	SA (m^2)	WP (m^2)
1	22.49	0.013	0.029	9.400	1.15E+04	1.17E+04	10.000	6.36E+03	1.36E+04
2	22.38	0.0127	0.028	9.392	1.15E+04	1.16E+04	9.957	6.33E+03	1.35E+04
3	22.29	0.0124	0.027	9.383	1.15E+04	1.16E+04	9.913	6.30E+03	1.35E+04
4	22.20	0.0121	0.026	9.371	1.14E+04	1.16E+04	9.865	6.27E+03	1.34E+04
5	22.12	0.0119	0.025	9.358	1.14E+04	1.16E+04	9.815	6.24E+03	1.33E+04
6	22.06	0.0117	0.024	9.343	1.14E+04	1.15E+04	9.763	6.21E+03	1.33E+04
7	22.00	0.0116	0.023	9.326	1.13E+04	1.15E+04	9.709	6.18E+03	1.32E+04
8	21.94	0.0115	0.022	9.308	1.13E+04	1.14E+04	9.652	6.14E+03	1.31E+04
9	21.90	0.0114	0.021	9.288	1.12E+04	1.14E+04	9.593	6.10E+03	1.30E+04
10	21.86	0.0113	0.021	9.266	1.12E+04	1.13E+04	9.532	6.06E+03	1.30E+04
11	21.83	0.0113	0.020	9.243	1.11E+04	1.13E+04	9.468	6.02E+03	1.29E+04
12	21.81	0.0113	0.019	9.217	1.11E+04	1.12E+04	9.402	5.98E+03	1.28E+04
13	21.79	0.0113	0.019	9.191	1.10E+04	1.11E+04	9.334	5.94E+03	1.27E+04
14	21.78	0.0114	0.018	9.162	1.09E+04	1.11E+04	9.264	5.89E+03	1.26E+04
15	21.77	0.0115	0.017	9.132	1.09E+04	1.10E+04	9.192	5.85E+03	1.25E+04
16	21.77	0.0116	0.017	9.100	1.08E+04	1.09E+04	9.117	5.80E+03	1.24E+04
17	21.78	0.0117	0.016	9.067	1.07E+04	1.08E+04	9.041	5.75E+03	1.23E+04
18	21.79	0.0119	0.016	9.032	1.06E+04	1.08E+04	8.962	5.70E+03	1.22E+04

DAY	Hidden Reservoir H (m)	SA (m^2)	WP (m^2)	Connections Temple Over	Palace Over	Hidden Over
1	2.000	9.45E+02	9.48E+02	0.00	0.00	0.00
2	2.199	1.14E+03	1.15E+03	0.00	0.00	0.00
3	2.355	1.31E+03	1.31E+03	0.00	0.00	0.00
4	2.483	1.46E+03	1.46E+03	0.00	0.00	0.00
5	2.592	1.59E+03	1.59E+03	0.00	0.00	0.00
6	2.686	1.70E+03	1.71E+03	0.00	0.00	0.00
7	2.766	1.81E+03	1.81E+03	0.00	0.00	0.00
8	2.837	1.90E+03	1.91E+03	0.00	0.00	0.00
9	2.898	1.98E+03	1.99E+03	0.00	0.00	0.00
10	2.952	2.06E+03	2.07E+03	0.00	0.00	0.00
11	2.998	2.12E+03	2.13E+03	0.00	0.00	0.00
12	3.038	2.18E+03	2.19E+03	0.00	0.00	0.00
13	3.072	2.23E+03	2.24E+03	0.00	0.00	0.00
14	3.101	2.27E+03	2.28E+03	0.00	0.00	0.00
15	3.125	2.31E+03	2.31E+03	0.00	0.00	0.00
16	3.144	2.34E+03	2.34E+03	0.00	0.00	0.00
17	3.159	2.36E+03	2.36E+03	0.00	0.00	0.00
18	3.169	2.37E+03	2.38E+03	0.00	0.00	0.00

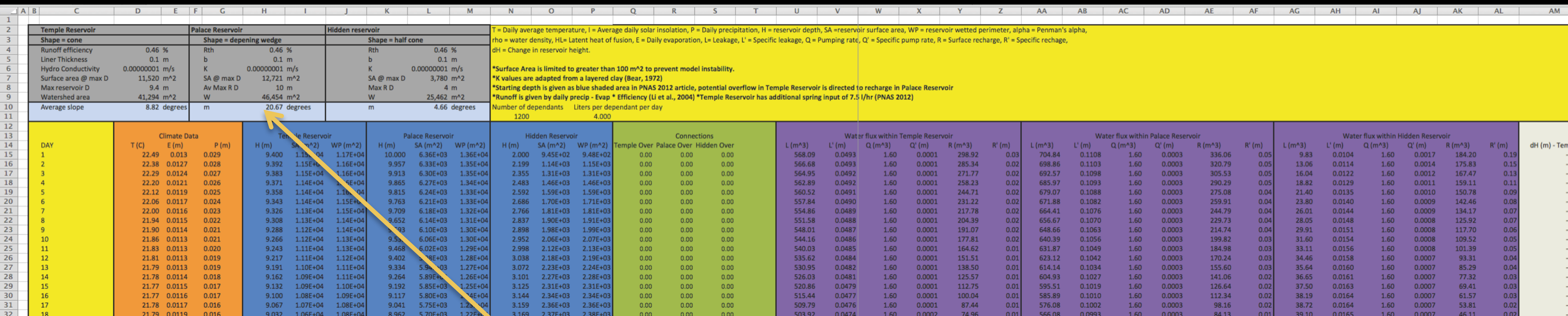
DAY	Water flux within Temple Reservoir L (m^3)	L' (m)	Q (m^3)	Q' (m)	R (m^3)	R' (m)
1	568.09	0.0493	1.60	0.0001	298.92	0.03
2	566.68	0.0493	1.60	0.0001	285.34	0.02
3	564.95	0.0492	1.60	0.0001	271.77	0.02
4	562.89	0.0492	1.60	0.0001	258.23	0.02
5	560.52	0.0491	1.60	0.0001	244.71	0.02
6	557.84	0.0490	1.60	0.0001	231.22	0.02
7	554.86	0.0489	1.60	0.0001	217.78	0.02
8	551.58	0.0488	1.60	0.0001	204.39	0.02
9	548.01	0.0487	1.60	0.0001	191.07	0.02
10	544.16	0.0486	1.60	0.0001	177.81	0.02
11	540.03	0.0485	1.60	0.0001	164.62	0.01
12	535.62	0.0484	1.60	0.0001	151.51	0.01
13	530.95	0.0482	1.60	0.0001	138.50	0.01
14	526.03	0.0481	1.60	0.0001	125.57	0.01
15	520.86	0.0479	1.60	0.0001	112.75	0.01
16	515.44	0.0477	1.60	0.0001	100.04	0.01
17	509.79	0.0476	1.60	0.0001	87.44	0.01
18	503.92	0.0474	1.60	0.0002	74.96	0.01

DAY	Water flux within Palace Reservoir L (m^3)	L' (m)	Q (m^3)	Q' (m)	R (m^3)	R' (m)
1	704.84	0.1108	1.60	0.0003	336.06	0.05
2	698.86	0.1103	1.60	0.0003	320.79	0.05
3	692.57	0.1098	1.60	0.0003	305.53	0.05
4	685.97	0.1093	1.60	0.0003	290.29	0.05
5	679.07	0.1088	1.60	0.0003	275.08	0.04
6	671.88	0.1082	1.60	0.0003	259.91	0.04
7	664.41	0.1076	1.60	0.0003	244.79	0.04
8	656.67	0.1070	1.60	0.0003	229.73	0.04
9	648.66	0.1063	1.60	0.0003	214.74	0.04
10	640.39	0.1056	1.60	0.0003	199.82	0.03
11	631.87	0.1049	1.60	0.0003	184.98	0.03
12	623.12	0.1042	1.60	0.0003	170.24	0.03
13	614.14	0.1034	1.60	0.0003	155.60	0.03
14	604.93	0.1027	1.60	0.0003	141.06	0.02
15	595.51	0.1019	1.60	0.0003	126.64	0.02
16	585.89	0.1010	1.60	0.0003	112.34	0.02
17	576.08	0.1002	1.60	0.0003	98.16	0.02
18	566.08	0.0993	1.60	0.0003	84.13	0.01

DAY	Water flux within Hidden Reservoir L (m^3)	L' (m)	Q (m^3)	Q' (m)	R (m^3)	R' (m)	dH (m) - Temple
1	9.83	0.0104	1.60	0.0017	184.20	0.19	-0.00
2	13.06	0.0114	1.60	0.0014	175.83	0.15	-0.00
3	16.04	0.0122	1.60	0.0012	167.47	0.13	-0.01
4	18.82	0.0129	1.60	0.0011	159.11	0.11	-0.01
5	21.40	0.0135	1.60	0.0010	150.78	0.09	-0.01
6	23.80	0.0140	1.60	0.0009	142.46	0.08	-0.01
7	26.01	0.0144	1.60	0.0009	134.17	0.07	-0.01
8	28.05	0.0148	1.60	0.0008	125.92	0.07	-0.02
9	29.91	0.0151	1.60	0.0008	117.70	0.06	-0.02
10	31.60	0.0154	1.60	0.0008	109.52	0.05	-0.02
11	33.11	0.0156	1.60	0.0008	101.39	0.05	-0.02
12	34.46	0.0158	1.60	0.0007	93.31	0.04	-0.02
13	35.64	0.0160	1.60	0.0007	85.29	0.04	-0.02
14	36.65	0.0161	1.60	0.0007	77.32	0.03	-0.03
15	37.50	0.0163	1.60	0.0007	69.41	0.03	-0.03
16	38.19	0.0164	1.60	0.0007	61.57	0.03	-0.03
17	38.72	0.0164	1.60	0.0007	53.81	0.02	-0.03
18	39.10	0.0165	1.60	0.0007	46.11	0.02	-0.03

The linked-reservoir model was translated into Excel using a series of geometric parameters, hydraulic equations, and linking equations. Overland flow into the reservoir is computed using a combination of watershed area, runoff efficiency, and precipitation-evapotranspiration. Reservoir seepage is calculated using Darcy's Law and a mean water depth. Reservoir surface area was caluclated using a geometric conversion from water depth. The surface area at each time interval is used to compute changes in water depth resulting from mass flux. Minimum surface areas prevent model instability and maximum depth values trigger overflow. Individual runs were allowed to run for up to 1,000 iterations or until convergence reached 0.1%

GSA 2012 – Florea – Model Input



Computes slope of reservoir basin using the surface area at maximum depth.

Average daily temperature, pan evaporation, and precipitation values from Tikal

GSA 2012 – Florea – Water Depth Computations

Temple Reservoir			**Palace Reservoir**			**Hidden reservoir**		
Shape = cone			**Shape = depening wedge**			**Shape = half cone**		
Runoff efficiency	0.46	%	Rth	0.46	%	Rth	0.46	%
Liner Thickness	0.1	m	b	0.1	m	b	0.1	m
Hydro Conductivity	0.00000001	m/s	K	0.00000001	m/s	K	0.00000001	m/s
Surface area @ max D	11,520	m^2	SA @ max D	12,721	m^2	SA @ max D	3,780	m^2
Max reservoir D	9.4	m	Av Max R D	10	m	Max R D	4	m
Watershed area	41,294	m^2	W	46,454	m^2	W	25,462	m^2
Average slope	8.82	degrees	m	20.67	degrees	m	4.66	degrees

T = Daily average temperature, I = Average daily solar insolation, P = Daily precipitation, H = reservoir depth, SA =reservoir surface area, WP = reservoir wetted perimeter, alpha = Penman's alpha, rho = water density, HL= Latent heat of fusion, E = Daily evaporation, L= Leakage, L' = Specific leakage, Q = Pumping rate, Q' = Specific pump rate, R = Surface recharge, R' = Specific rechage, dH = Change in reservoir height.

***Surface Area is limited to greater than 100 m^2 to prevent model instability.**
***K values are adapted from a layered clay (Bear, 1972)**
***Starting depth is given as blue shaded area in PNAS 2012 article, potential overflow in Temple Reservoir is directed to recharge in Palace Reservoir**
***Runoff is given by daily precip - Evap * Efficiency (Li et al., 2004) *Temple Reservoir has additional spring input of 7.5 l/hr (PNAS 2012)**

Number of dependants	Liters per dependant per day
1200	4.000

	Climate Data			Temple Reservoir			Palace Reservoir			Hidden Reservoir			Connections		
DAY	T (C)	E (m)	P (m)	H (m)	SA (m^2)	WP (m^2)	H (m)	SA (m^2)	WP (m^2)	H (m)	SA (m^2)	WP (m^2)	Temple Over	Palace Over	Hidden Over
1	22.49	0.013	0.029	9.400	1.15E+04	1.17E+04	10.000	6.36E+03	1.36E+04	2.000	9.45E+02	9.48E+02	0.00	0.00	0.00
2	22.38	0.0127	0.028	9.392	1.15E+04	1.16E+04	9.957	6.33E+03	1.35E+04	2.199	1.14E+03	1.15E+03	0.00	0.00	0.00
3	22.29	0.0124	0.027	9.383	1.15E+04	1.16E+04	9.913	6.30E+03	1.35E+04	2.355	1.31E+03	1.31E+03	0.00	0.00	0.00
4	22.20	0.0121	0.026	9.371	1.14E+04	1.16E+04	9.865	6.27E+03	1.34E+04	2.483	1.46E+03	1.46E+03	0.00	0.00	0.00
5	22.12	0.0119	0.025	9.358	1.14E+04	1.16E+04	9.815	6.24E+03	1.33E+04	2.592	1.59E+03	1.59E+03	0.00	0.00	0.00
6	22.06	0.0117	0.024	9.343	1.14E+04	1.15E+04	9.763	6.21E+03	1.33E+04	2.686	1.70E+03	1.71E+03	0.00	0.00	0.00
7	22.00	0.0116	0.023	9.326	1.13E+04	1.15E+04	9.709	6.18E+03	1.32E+04	2.766	1.81E+03	1.81E+03	0.00	0.00	0.00
8	21.94	0.0115	0.022	9.308	1.13E+04	1.14E+04	9.652	6.14E+03	1.31E+04	2.837	1.90E+03	1.91E+03	0.00	0.00	0.00
9	21.90	0.0114	0.021	9.288	1.12E+04	1.14E+04	9.593	6.10E+03	1.30E+04	2.898	1.98E+03	1.99E+03	0.00	0.00	0.00
10	21.86	0.0113	0.021	9.266	1.12E+04	1.13E+04	9.532	6.06E+03	1.30E+04	2.952	2.06E+03	2.07E+03	0.00	0.00	0.00
11	21.83	0.0113	0.020	9.243	1.11E+04	1.13E+04	9.468	6.02E+03	1.29E+04	2.998	2.12E+03	2.13E+03	0.00	0.00	0.00
12	21.81	0.0113	0.019	9.217	1.11E+04	1.12E+04	9.402	5.98E+03	1.28E+04	3.038	2.18E+03	2.19E+03	0.00	0.00	0.00
13	21.79	0.0113	0.019	9.191	1.10E+04	1.11E+04	9.334	5.94E+03	1.27E+04	3.072	2.23E+03	2.24E+03	0.00	0.00	0.00
14	21.78	0.0114	0.018	9.162	1.09E+04	1.11E+04	9.264	5.89E+03	1.26E+04	3.101	2.27E+03	2.28E+03	0.00	0.00	0.00
15	21.77	0.0115	0.017	9.132	1.09E+04	1.10E+04	9.192	5.85E+03	1.25E+04	3.125	2.31E+03	2.31E+03	0.00	0.00	0.00
16	21.77	0.0116	0.017	9.100	1.08E+04	1.09E+04	9.117	5.80E+03	1.24E+04	3.144	2.34E+03	2.34E+03	0.00	0.00	0.00
17	21.78	0.0117	0.016	9.067	1.07E+04	1.08E+04	9.041	5.75E+03	1.23E+04	3.159	2.36E+03	2.36E+03	0.00	0.00	0.00
18	21.79	0.0119	0.016	9.032	1.06E+04	1.08E+04	8.962	5.70E+03	1.22E+04	3.169	2.37E+03	2.38E+03	0.00	0.00	0.00

	Water flux within Temple Reservoir						Water flux within Palace Reservoir					
DAY	L (m^3)	L' (m)	Q (m^3)	Q' (m)	R (m^3)	R' (m)	L (m^3)	L' (m)	Q (m^3)	Q' (m)	R (m^3)	R' (m)
1	568.09	0.0493	1.60	0.0001	298.92	0.03	704.84	0.1108	1.60	0.0003	336.06	0.05
2	566.68	0.0493	1.60	0.0001	285.34	0.02	698.86	0.1103	1.60	0.0003	320.79	0.05
3	564.95	0.0492	1.60	0.0001	271.77	0.02	692.57	0.1098	1.60	0.0003	305.53	0.05
4	562.89	0.0492	1.60	0.0001	258.23	0.02	685.97	0.1093	1.60	0.0003	290.29	0.05
5	560.52	0.0491	1.60	0.0001	244.71	0.02	679.07	0.1088	1.60	0.0003	275.08	0.04
6	557.84	0.0490	1.60	0.0001	231.22	0.02	671.88	0.1082	1.60	0.0003	259.91	0.04
7	554.86	0.0489	1.60	0.0001	217.78	0.02	664.41	0.1076	1.60	0.0003	244.79	0.04
8	551.58	0.0488	1.60	0.0001	204.39	0.02	656.67	0.1070	1.60	0.0003	229.73	0.04
9	548.01	0.0487	1.60	0.0001	191.07	0.02	648.66	0.1063	1.60	0.0003	214.74	0.04
10	544.16	0.0486	1.60	0.0001	177.81	0.02	640.39	0.1056	1.60	0.0003	199.82	0.03
11	540.03	0.0485	1.60	0.0001	164.62	0.01	631.87	0.1049	1.60	0.0003	184.98	0.03
12	535.62	0.0484	1.60	0.0001	151.51	0.01	623.12	0.1042	1.60	0.0003	170.24	0.03
13	530.95	0.0482	1.60	0.0001	138.50	0.01	614.14	0.1034	1.60	0.0003	155.60	0.03
14	526.03	0.0481	1.60	0.0001	125.57	0.01	604.93	0.1027	1.60	0.0003	141.06	0.02
15	520.86	0.0479	1.60	0.0001	112.75	0.01	595.51	0.1019	1.60	0.0003	126.64	0.02
16	515.44	0.0477	1.60	0.0001	100.04	0.01	585.89	0.1010	1.60	0.0003	112.34	0.02
17	509.79	0.0476	1.60	0.0001	87.44	0.01	576.08	0.1002	1.60	0.0003	98.16	0.02
18	503.92	0.0474	1.60	0.0002	74.96	0.01	566.08	0.0993	1.60	0.0003	84.13	0.01

	Water flux within Hidden Reservoir						
DAY	L (m^3)	L' (m)	Q (m^3)	Q' (m)	R (m^3)	R' (m)	dH (m) - Temple
1	9.83	0.0104	1.60	0.0017	184.20	0.19	-0.00
2	13.06	0.0114	1.60	0.0014	175.83	0.15	-0.00
3	16.04	0.0122	1.60	0.0012	167.47	0.13	-0.01
4	18.82	0.0129	1.60	0.0011	159.11	0.11	-0.01
5	21.40	0.0135	1.60	0.0010	150.78	0.09	-0.01
6	23.80	0.0140	1.60	0.0009	142.46	0.08	-0.01
7	26.01	0.0144	1.60	0.0009	134.17	0.07	-0.01
8	28.05	0.0148	1.60	0.0008	125.92	0.07	-0.02
9	29.91	0.0151	1.60	0.0008	117.70	0.06	-0.02
10	31.60	0.0154	1.60	0.0008	109.52	0.05	-0.02
11	33.11	0.0156	1.60	0.0008	101.39	0.05	-0.02
12	34.46	0.0158	1.60	0.0007	93.31	0.04	-0.02
13	35.64	0.0160	1.60	0.0007	85.29	0.04	-0.02
14	36.65	0.0161	1.60	0.0007	77.32	0.03	-0.03
15	37.50	0.0163	1.60	0.0007	69.41	0.03	-0.03
16	38.19	0.0164	1.60	0.0007	61.57	0.03	-0.03
17	38.72	0.0164	1.60	0.0007	53.81	0.02	-0.03
18	39.10	0.0165	1.60	0.0007	46.11	0.02	-0.03

Computes new WL

Computes new SA

Computes new WP

Computed water level, surface area, and wetted perimeter

```
H=IF(H+AM<0,0,IF(H+AM>$D$8,$D$8,H+AM))
I=IF(Pi*((H/TAN(($D$10*Pi)/180))^2)<100,100,Pi*((H/TAN(($D$10*Pi)/180))^2))
J=2*(K/SIN($H$10*Pi/180))*240
K=IF(K+AN<0,0,IF(K+AN>$H$8,$H$8,K+AN))
L=IF(((K/TAN(($H$10*Pi)/180)))*240<100,100,((K/TAN(($H$10*Pi)/180)))*240)
M=2*(K/SIN($H$10*Pi/180))*240
N=IF(N+AO<0,0,IF(N+AO>$L$8,$L$8,N+AO))
O=IF(((Pi*((N/TAN(($L$10*Pi)/180))^2))/2)<100,100,(Pi*((N/TAN(($L$10*Pi)/180))^2))/2)
P=Pi*((N)/TAN(($L$10*Pi)/180))*((N)/SIN(($L$10*Pi)/180))/2+(N*SIN($L$10*Pi)/180)*N
```

GSA 2012 – Florea – Linking Reservoirs

Temple Reservoir			Palace Reservoir			Hidden reservoir		
Shape = cone			Shape = depening wedge			Shape = half cone		
Runoff efficiency	0.46	%	Rth	0.46	%	Rth	0.46	%
Liner Thickness	0.1	m	b	0.1	m	b	0.1	m
Hydro Conductivity	0.00000001	m/s	K	0.00000001	m/s	K	0.00000001	m/s
Surface area @ max D	11,520	m^2	SA @ max D	12,721	m^2	SA @ max D	3,780	m^2
Max reservoir D	9.4	m	Av Max R D	10	m	Max R D	4	m
Watershed area	41,294	m^2	W	46,454	m^2	W	25,462	m^2
Average slope	8.82	degrees	m	20.67	degrees	m	4.66	degrees

T = Daily average temperature, I = Average daily solar insolation, P = Daily precipitation, H = reservoir depth, SA =reservoir surface area, WP = reservoir wetted perimeter, alpha = Penman's alpha,
rho = water density, HL= Latent heat of fusion, E = Daily evaporation, L= Leakage, L' = Specific leakage, Q = Pumping rate, Q' = Specific pump rate, R = Surface recharge, R' = Specific rechage,
dH = Change in reservoir height.

***Surface Area is limited to greater than 100 m^2 to prevent model instability.**
***K values are adapted from a layered clay (Bear, 1972)**
***Starting depth is given as blue shaded area in PNAS 2012 article, potential overflow in Temple Reservoir is directed to recharge in Palace Reservoir**
***Runoff is given by daily precip - Evap * Efficiency (Li et al., 2004) *Temple Reservoir has additional spring input of 7.5 l/hr (PNAS 2012)**

Number of dependants	Liters per dependant per day
1200	4.000

	Climate Data			Temple Reservoir			Palace Reservoir		
DAY	T (C)	E (m)	P (m)	H (m)	SA (m^2)	WP (m^2)	H (m)	SA (m^2)	WP (m^2)
1	22.49	0.013	0.029	9.400	1.15E+04	1.17E+04	10.000	6.36E+03	1.36E+04
2	22.38	0.0127	0.028	9.392	1.15E+04	1.16E+04	9.957	6.33E+03	1.35E+04
3	22.29	0.0124	0.027	9.383	1.15E+04	1.16E+04	9.913	6.30E+03	1.35E+04
4	22.20	0.0121	0.026	9.371	1.14E+04	1.16E+04	9.865	6.27E+03	1.34E+04
5	22.12	0.0119	0.025	9.358	1.14E+04	1.16E+04	9.815	6.24E+03	1.33E+04
6	22.06	0.0117	0.024	9.343	1.14E+04	1.15E+04	9.763	6.21E+03	1.33E+04
7	22.00	0.0116	0.023	9.326	1.13E+04	1.15E+04	9.709	6.18E+03	1.32E+04
8	21.94	0.0115	0.022	9.308	1.13E+04	1.14E+04	9.652	6.14E+03	1.31E+04
9	21.90	0.0114	0.021	9.288	1.12E+04	1.14E+04	9.593	6.10E+03	1.30E+04
10	21.86	0.0113	0.021	9.266	1.12E+04	1.13E+04	9.532	6.06E+03	1.30E+04
11	21.83	0.0113	0.020	9.243	1.11E+04	1.13E+04	9.468	6.02E+03	1.29E+04
12	21.81	0.0113	0.019	9.217	1.11E+04	1.12E+04	9.402	5.98E+03	1.28E+04
13	21.79	0.0113	0.019	9.191	1.10E+04	1.11E+04	9.334	5.94E+03	1.27E+04
14	21.78	0.0114	0.018	9.162	1.09E+04	1.11E+04	9.264	5.89E+03	1.26E+04
15	21.77	0.0115	0.017	9.132	1.09E+04	1.10E+04	9.192	5.85E+03	1.25E+04
16	21.77	0.0116	0.017	9.100	1.08E+04	1.09E+04	9.117	5.80E+03	1.24E+04
17	21.78	0.0117	0.016	9.067	1.07E+04	1.08E+04	9.041	5.75E+03	1.23E+04
18	21.79	0.0119	0.016	9.032	1.06E+04	1.08E+04	8.962	5.70E+03	1.22E+04

	Hidden Reservoir			Connections			Water flux within Temple Reservoir					
DAY	H (m)	SA (m^2)	WP (m^2)	Temple Over	Palace Over	Hidden Over	L (m^3)	L' (m)	Q (m^3)	Q' (m)	R (m^3)	R' (m)
1	2.000	9.45E+02	9.48E+02	0.00	0.00	0.00	568.09	0.0493	1.60	0.0001	298.92	0.03
2	2.199	1.14E+03	1.15E+03	0.00	0.00	0.00	566.68	0.0493	1.60	0.0001	285.34	0.02
3	2.355	1.31E+03	1.31E+03	0.00	0.00	0.00	564.95	0.0492	1.60	0.0001	271.77	0.02
4	2.483	1.46E+03	1.46E+03	0.00	0.00	0.00	562.89	0.0492	1.60	0.0001	258.23	0.02
5	2.592	1.59E+03	1.59E+03	0.00	0.00	0.00	560.52	0.0491	1.60	0.0001	244.71	0.02
6	2.686	1.70E+03	1.71E+03	0.00	0.00	0.00	557.84	0.0490	1.60	0.0001	231.22	0.02
7	2.766	1.81E+03	1.81E+03	0.00	0.00	0.00	554.86	0.0489	1.60	0.0001	217.78	0.02
8	2.837	1.90E+03	1.91E+03	0.00	0.00	0.00	551.58	0.0488	1.60	0.0001	204.39	0.02
9	2.898	1.98E+03	1.99E+03	0.00	0.00	0.00	548.01	0.0487	1.60	0.0001	191.07	0.02
10	2.952	2.06E+03	2.07E+03	0.00	0.00	0.00	544.16	0.0486	1.60	0.0001	177.81	0.02
11	2.998	2.12E+03	2.13E+03	0.00	0.00	0.00	540.03	0.0485	1.60	0.0001	164.62	0.01
12	3.038	2.18E+03	2.19E+03	0.00	0.00	0.00	535.62	0.0484	1.60	0.0001	151.51	0.01
13	3.072	2.23E+03	2.24E+03	0.00	0.00	0.00	530.95	0.0482	1.60	0.0001	138.50	0.01
14	3.101	2.27E+03	2.28E+03	0.00	0.00	0.00	526.03	0.0481	1.60	0.0001	125.57	0.01
15	3.125	2.31E+03	2.31E+03	0.00	0.00	0.00	520.86	0.0479	1.60	0.0001	112.75	0.01
16	3.144	2.34E+03	2.34E+03	0.00	0.00	0.00	515.44	0.0477	1.60	0.0001	100.04	0.01
17	3.159	2.36E+03	2.36E+03	0.00	0.00	0.00	509.79	0.0476	1.60	0.0001	87.44	0.01
18	3.169	2.37E+03	2.38E+03	0.00	0.00	0.00	503.92	0.0474	1.60	0.0002	74.96	0.01

	Water flux within Palace Reservoir						Water flux within Hidden Reservoir						
DAY	L (m^3)	L' (m)	Q (m^3)	Q' (m)	R (m^3)	R' (m)	L (m^3)	L' (m)	Q (m^3)	Q' (m)	R (m^3)	R' (m)	dH (m) - Temple
1	704.84	0.1108	1.60	0.0003	336.06	0.05	9.83	0.0104	1.60	0.0017	184.20	0.19	-0.00
2	698.86	0.1103	1.60	0.0003	320.79	0.05	13.06	0.0114	1.60	0.0014	175.83	0.15	-0.00
3	692.57	0.1098	1.60	0.0003	305.53	0.05	16.04	0.0122	1.60	0.0012	167.47	0.13	-0.01
4	685.97	0.1093	1.60	0.0003	290.29	0.05	18.82	0.0129	1.60	0.0011	159.11	0.11	-0.01
5	679.07	0.1088	1.60	0.0003	275.08	0.04	21.40	0.0135	1.60	0.0010	150.78	0.09	-0.01
6	671.88	0.1082	1.60	0.0003	259.91	0.04	23.80	0.0140	1.60	0.0009	142.46	0.08	-0.01
7	664.41	0.1076	1.60	0.0003	244.79	0.04	26.01	0.0144	1.60	0.0009	134.17	0.07	-0.01
8	656.67	0.1070	1.60	0.0003	229.73	0.04	28.05	0.0148	1.60	0.0008	125.92	0.07	-0.02
9	648.66	0.1063	1.60	0.0003	214.74	0.04	29.91	0.0151	1.60	0.0008	117.70	0.06	-0.02
10	640.39	0.1056	1.60	0.0003	199.82	0.03	31.60	0.0154	1.60	0.0008	109.52	0.05	-0.02
11	631.87	0.1049	1.60	0.0003	184.98	0.03	33.11	0.0156	1.60	0.0008	101.39	0.05	-0.02
12	623.12	0.1042	1.60	0.0003	170.24	0.03	34.46	0.0158	1.60	0.0007	93.31	0.04	-0.02
13	614.14	0.1034	1.60	0.0003	155.60	0.03	35.64	0.0160	1.60	0.0007	85.29	0.04	-0.02
14	604.93	0.1027	1.60	0.0003	141.06	0.02	36.65	0.0161	1.60	0.0007	77.32	0.03	-0.03
15	595.51	0.1019	1.60	0.0003	126.64	0.02	37.50	0.0163	1.60	0.0007	69.41	0.03	-0.03
16	585.89	0.1010	1.60	0.0003	112.34	0.02	38.19	0.0164	1.60	0.0007	61.57	0.03	-0.03
17	576.08	0.1002	1.60	0.0003	98.16	0.02	38.72	0.0164	1.60	0.0007	53.81	0.02	-0.03
18	566.08	0.0993	1.60	0.0003	84.13	0.01	39.10	0.0165	1.60	0.0007	46.11	0.02	-0.03

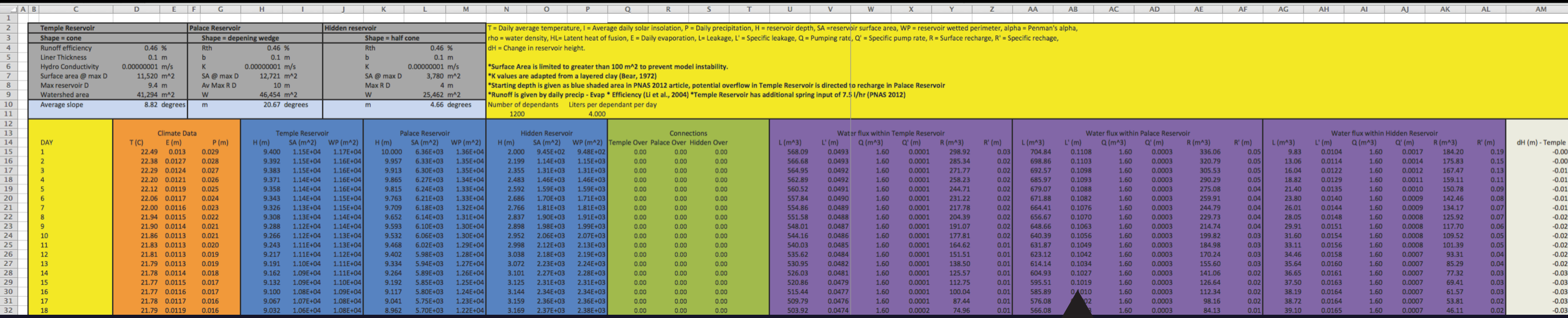
Volume of reservoir overflow

Q=IF(H=$D$8,AM*$D$7,0)

R=IF(K=$H$8,AN*$H$7,0)

S=IF(N=$L$8,AO*$L$7,0)

GSA 2012 – Florea – Flux Computations



Computed seepage from base of reservoir, pumping rate, and recharge

Darcy's Law — $U=(\$D\$6*J*(H*0.6)*(1/\$D\$5))*86400$

WL Change — $V=U/((I+I_{i+1})*0.6)$

Pump rate — $W=\$N\$11/3*(\$P\$11/1000)$

WL Change — $X=W/((I+I_{i+1})*0.6)$

Recharge — $Y=IF(((G-E))<0,0,((G-E)*\$D\$4*\$D\$9))+(7.5/1000)*24$

WL Change — $Z=Y/((I+I_{i+1})*0.6)$

GSA 2012 – Florea – Mass Balance Computation

Temple Reservoir			Palace Reservoir			Hidden reservoir		
Shape = cone			Shape = depening wedge			Shape = half cone		
Runoff efficiency	0.46	%	Rth	0.46	%	Rth	0.46	%
Liner Thickness	0.1	m	b	0.1	m	b	0.1	m
Hydro Conductivity	0.00000001	m/s	K	0.00000001	m/s	K	0.00000001	m/s
Surface area @ max D	11,520	m^2	SA @ max D	12,721	m^2	SA @ max D	3,780	m^2
Max reservoir D	9.4	m	Av Max R D	10	m	Max R D	4	m
Watershed area	41,294	m^2	W	46,454	m^2	W	25,462	m^2
Average slope	8.82	degrees	m	20.67	degrees	m	4.66	degrees

T = Daily average temperature, I = Average daily solar insolation, P = Daily precipitation, H = reservoir depth, SA =reservoir surface area, WP = reservoir wetted perimeter, alpha = Penman's alpha,
rho = water density, HL= Latent heat of fusion, E = Daily evaporation, L= Leakage, L' = Specific leakage, Q = Pumping rate, Q' = Specific pump rate, R = Surface recharge, R' = Specific rechage,
dH = Change in reservoir height.

***Surface Area is limited to greater than 100 m^2 to prevent model instability.**
***K values are adapted from a layered clay (Bear, 1972)**
***Starting depth is given as blue shaded area in PNAS 2012 article, potential overflow in Temple Reservoir is directed to recharge in Palace Reservoir**
***Runoff is given by daily precip - Evap * Efficiency (Li et al., 2004) *Temple Reservoir has additional spring input of 7.5 l/hr (PNAS 2012)**

Number of dependants	Liters per dependant per day
1200	4.000

	Climate Data			Temple Reservoir			Palace Reservoir		
DAY	T (C)	E (m)	P (m)	H (m)	SA (m^2)	WP (m^2)	H (m)	SA (m^2)	WP (m^2)
1	22.49	0.013	0.029	9.400	1.15E+04	1.17E+04	10.000	6.36E+03	1.36E+04
2	22.38	0.0127	0.028	9.392	1.15E+04	1.16E+04	9.957	6.33E+03	1.35E+04
3	22.29	0.0124	0.027	9.383	1.15E+04	1.16E+04	9.913	6.30E+03	1.35E+04
4	22.20	0.0121	0.026	9.371	1.14E+04	1.16E+04	9.865	6.27E+03	1.34E+04
5	22.12	0.0119	0.025	9.358	1.14E+04	1.16E+04	9.815	6.24E+03	1.33E+04
6	22.06	0.0117	0.024	9.343	1.14E+04	1.15E+04	9.763	6.21E+03	1.33E+04
7	22.00	0.0116	0.023	9.326	1.13E+04	1.15E+04	9.709	6.18E+03	1.32E+04
8	21.94	0.0115	0.022	9.308	1.13E+04	1.14E+04	9.652	6.14E+03	1.31E+04
9	21.90	0.0114	0.021	9.288	1.12E+04	1.14E+04	9.593	6.10E+03	1.30E+04
10	21.86	0.0113	0.021	9.266	1.12E+04	1.13E+04	9.532	6.06E+03	1.30E+04
11	21.83	0.0113	0.020	9.243	1.11E+04	1.13E+04	9.468	6.02E+03	1.29E+04
12	21.81	0.0113	0.019	9.217	1.11E+04	1.12E+04	9.402	5.98E+03	1.28E+04
13	21.79	0.0113	0.019	9.191	1.10E+04	1.11E+04	9.334	5.94E+03	1.27E+04
14	21.78	0.0114	0.018	9.162	1.09E+04	1.11E+04	9.264	5.89E+03	1.26E+04
15	21.77	0.0115	0.017	9.132	1.09E+04	1.10E+04	9.192	5.85E+03	1.25E+04
16	21.77	0.0116	0.017	9.100	1.08E+04	1.09E+04	9.117	5.80E+03	1.24E+04
17	21.78	0.0117	0.016	9.067	1.07E+04	1.08E+04	9.041	5.75E+03	1.23E+04
18	21.79	0.0119	0.016	9.032	1.06E+04	1.08E+04	8.962	5.70E+03	1.22E+04

	Hidden Reservoir			Connections		
DAY	H (m)	SA (m^2)	WP (m^2)	Temple Over	Palace Over	Hidden Over
1	2.000	9.45E+02	9.48E+02	0.00	0.00	0.00
2	2.199	1.14E+03	1.15E+03	0.00	0.00	0.00
3	2.355	1.31E+03	1.31E+03	0.00	0.00	0.00
4	2.483	1.46E+03	1.46E+03	0.00	0.00	0.00
5	2.592	1.59E+03	1.59E+03	0.00	0.00	0.00
6	2.686	1.70E+03	1.71E+03	0.00	0.00	0.00
7	2.766	1.81E+03	1.81E+03	0.00	0.00	0.00
8	2.837	1.90E+03	1.91E+03	0.00	0.00	0.00
9	2.898	1.98E+03	1.99E+03	0.00	0.00	0.00
10	2.952	2.06E+03	2.07E+03	0.00	0.00	0.00
11	2.998	2.12E+03	2.13E+03	0.00	0.00	0.00
12	3.038	2.18E+03	2.19E+03	0.00	0.00	0.00
13	3.072	2.23E+03	2.24E+03	0.00	0.00	0.00
14	3.101	2.27E+03	2.28E+03	0.00	0.00	0.00
15	3.125	2.31E+03	2.31E+03	0.00	0.00	0.00
16	3.144	2.34E+03	2.34E+03	0.00	0.00	0.00
17	3.159	2.36E+03	2.36E+03	0.00	0.00	0.00
18	3.169	2.37E+03	2.38E+03	0.00	0.00	0.00

	Water flux within Temple Reservoir					
DAY	L (m^3)	L' (m)	Q (m^3)	Q' (m)	R (m^3)	R' (m)
1	568.09	0.0493	1.60	0.0001	298.92	0.03
2	566.68	0.0493	1.60	0.0001	285.34	0.02
3	564.95	0.0492	1.60	0.0001	271.77	0.02
4	562.89	0.0492	1.60	0.0001	258.23	0.02
5	560.52	0.0491	1.60	0.0001	244.71	0.02
6	557.84	0.0490	1.60	0.0001	231.22	0.02
7	554.86	0.0489	1.60	0.0001	217.78	0.02
8	551.58	0.0488	1.60	0.0001	204.39	0.02
9	548.01	0.0487	1.60	0.0001	191.07	0.02
10	544.16	0.0486	1.60	0.0001	177.81	0.02
11	540.03	0.0485	1.60	0.0001	164.62	0.01
12	535.62	0.0484	1.60	0.0001	151.51	0.01
13	530.95	0.0482	1.60	0.0001	138.50	0.01
14	526.03	0.0481	1.60	0.0001	125.57	0.01
15	520.86	0.0479	1.60	0.0001	112.75	0.01
16	515.44	0.0477	1.60	0.0001	100.04	0.01
17	509.79	0.0476	1.60	0.0001	87.44	0.01
18	503.92	0.0474	1.60	0.0002	74.96	0.01

	Water flux within Palace Reservoir					
DAY	L (m^3)	L' (m)	Q (m^3)	Q' (m)	R (m^3)	R' (m)
1	704.84	0.1108	1.60	0.0003	336.06	0.05
2	698.86	0.1103	1.60	0.0003	320.79	0.05
3	692.57	0.1098	1.60	0.0003	305.53	0.05
4	685.97	0.1093	1.60	0.0003	290.29	0.05
5	679.07	0.1088	1.60	0.0003	275.08	0.04
6	671.88	0.1082	1.60	0.0003	259.91	0.04
7	664.41	0.1076	1.60	0.0003	244.79	0.04
8	656.67	0.1070	1.60	0.0003	229.73	0.04
9	648.66	0.1063	1.60	0.0003	214.74	0.04
10	640.39	0.1056	1.60	0.0003	199.82	0.03
11	631.87	0.1049	1.60	0.0003	184.98	0.03
12	623.12	0.1042	1.60	0.0003	170.24	0.03
13	614.14	0.1034	1.60	0.0003	155.60	0.03
14	604.93	0.1027	1.60	0.0003	141.06	0.02
15	595.51	0.1019	1.60	0.0003	126.64	0.02
16	585.89	0.1010	1.60	0.0003	112.34	0.02
17	576.08	0.1002	1.60	0.0003	98.16	0.02
18	566.08	0.0993	1.60	0.0003	84.13	0.01

	Water flux within Hidden Reservoir						
DAY	L (m^3)	L' (m)	Q (m^3)	Q' (m)	R (m^3)	R' (m)	dH (m) - Temple
1	9.83	0.0104	1.60	0.0017	184.20	0.19	-0.00
2	13.06	0.0114	1.60	0.0014	175.83	0.15	-0.00
3	16.04	0.0122	1.60	0.0012	167.47	0.13	-0.01
4	18.82	0.0129	1.60	0.0011	159.11	0.11	-0.01
5	21.40	0.0135	1.60	0.0010	150.78	0.09	-0.01
6	23.80	0.0140	1.60	0.0009	142.46	0.08	-0.01
7	26.01	0.0144	1.60	0.0009	134.17	0.07	-0.01
8	28.05	0.0148	1.60	0.0008	125.92	0.07	-0.02
9	29.91	0.0151	1.60	0.0008	117.70	0.06	-0.02
10	31.60	0.0154	1.60	0.0008	109.52	0.05	-0.02
11	33.11	0.0156	1.60	0.0008	101.39	0.05	-0.02
12	34.46	0.0158	1.60	0.0007	93.31	0.04	-0.02
13	35.64	0.0160	1.60	0.0007	85.29	0.04	-0.02
14	36.65	0.0161	1.60	0.0007	77.32	0.03	-0.03
15	37.50	0.0163	1.60	0.0007	69.41	0.03	-0.03
16	38.19	0.0164	1.60	0.0007	61.57	0.03	-0.03
17	38.72	0.0164	1.60	0.0007	53.81	0.02	-0.03
18	39.10	0.0165	1.60	0.0007	46.11	0.02	-0.03

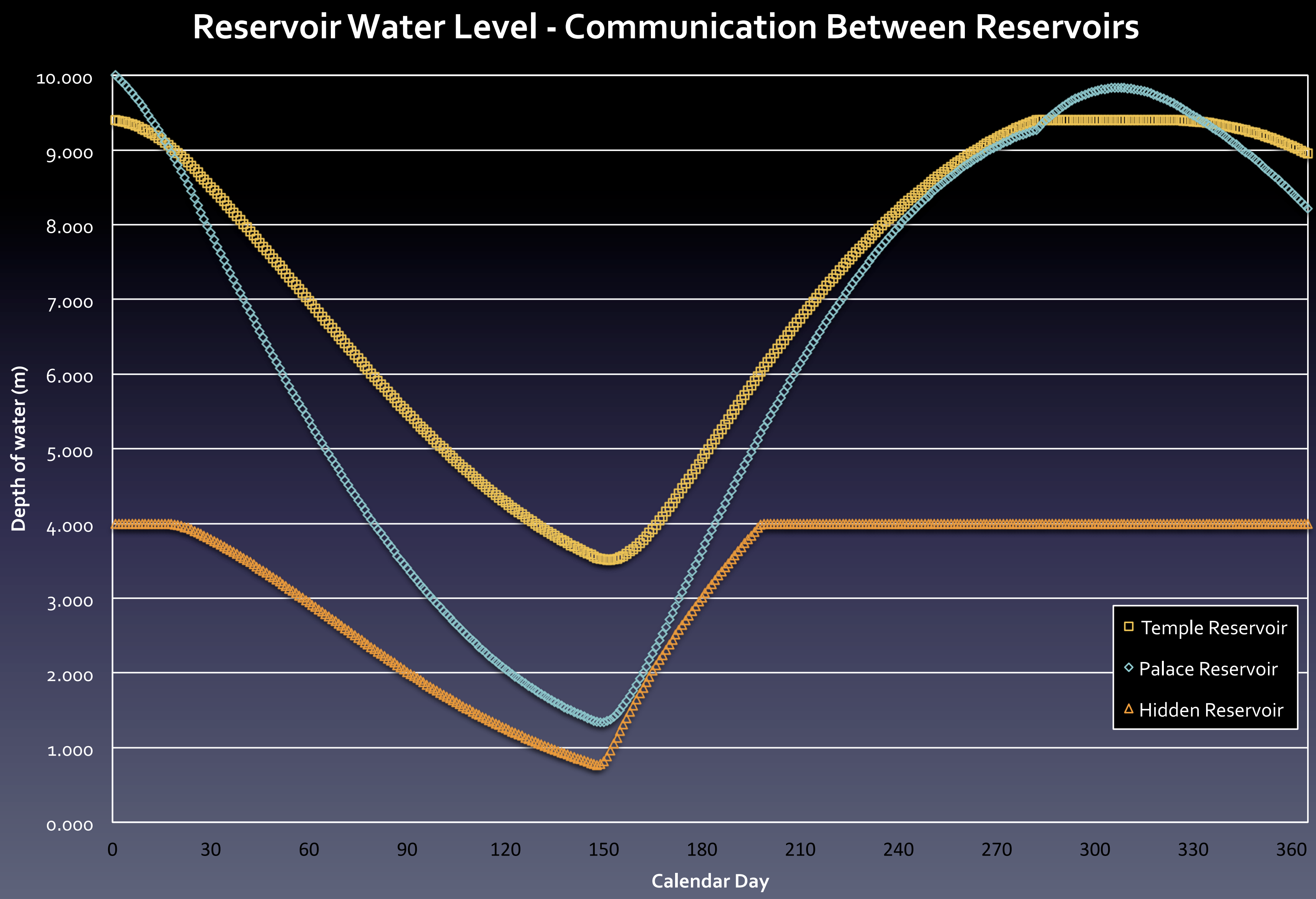
Preip + Runoff – Evapotrans – Leakage - Pumping

P + R – ET – L – Q

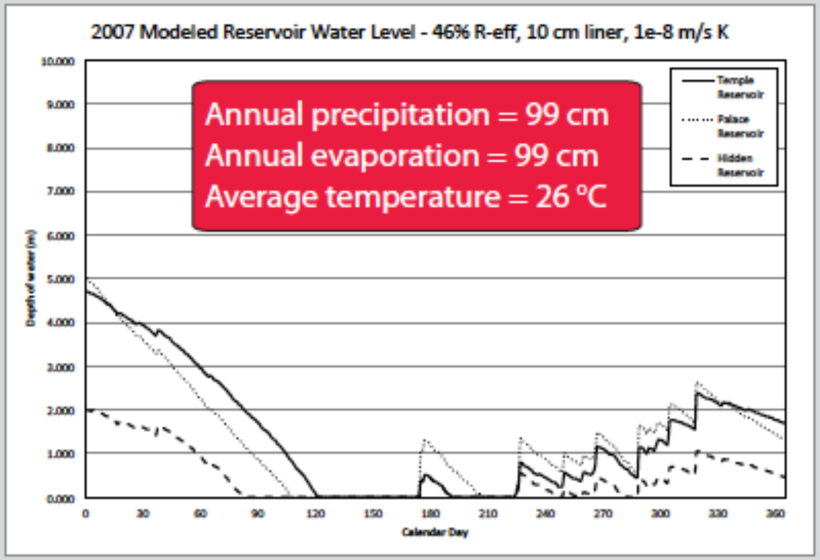
Change in water height in reservoir

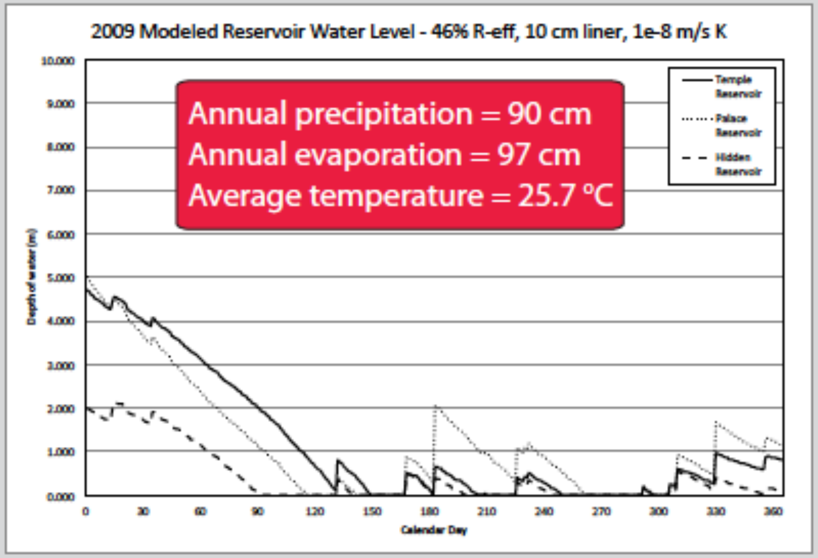
AM=G+Z-E-V-X
AN=G+AF-E-AD-AB
AO=G+AL-E-AH-AJ
AP=IF(S<0,0,S*1000)

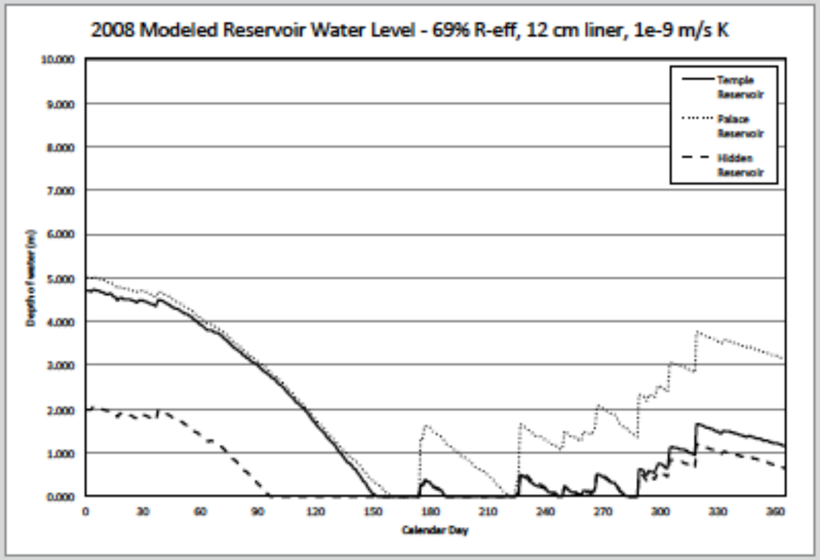
GSA 2012 – Florea – Results (Average Climate Data)

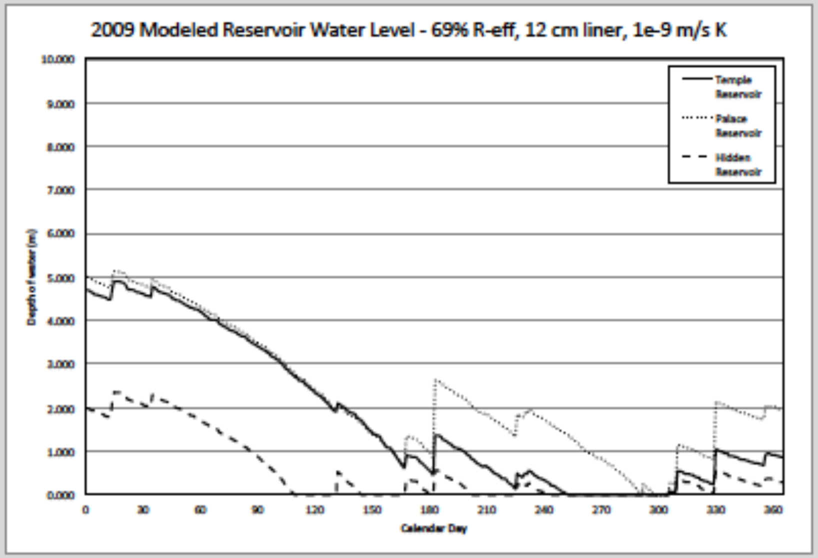


GSA 2012 – Florea – Results (El Nino Years)

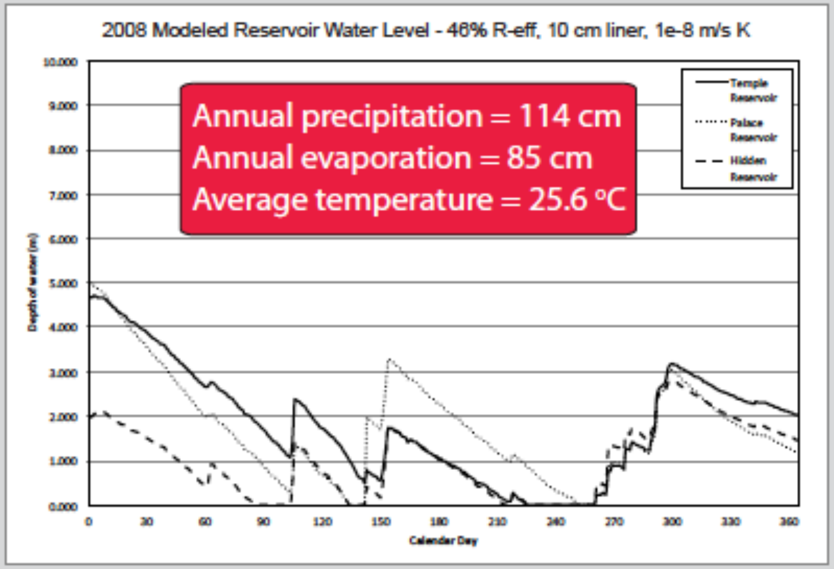


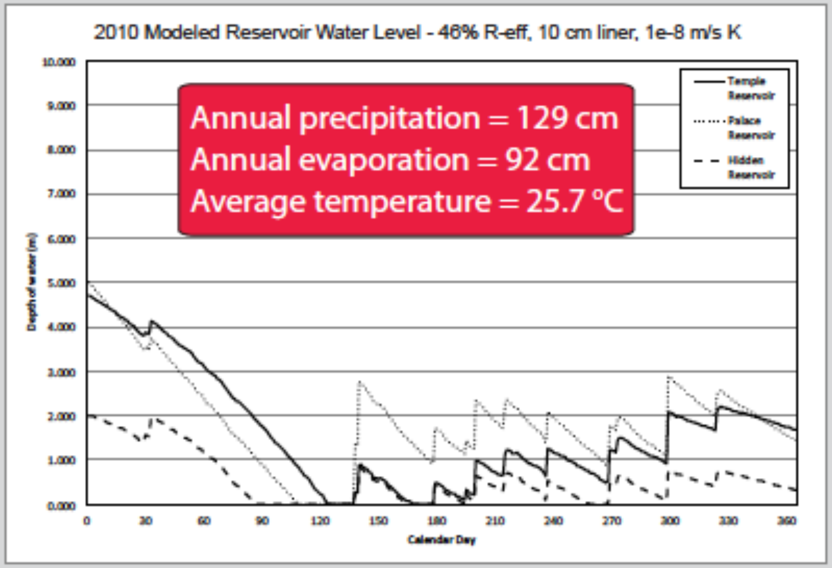


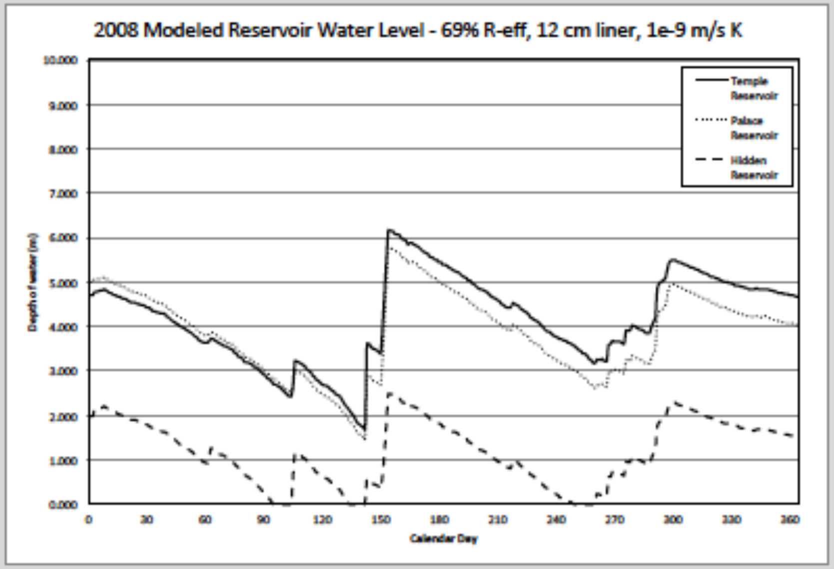


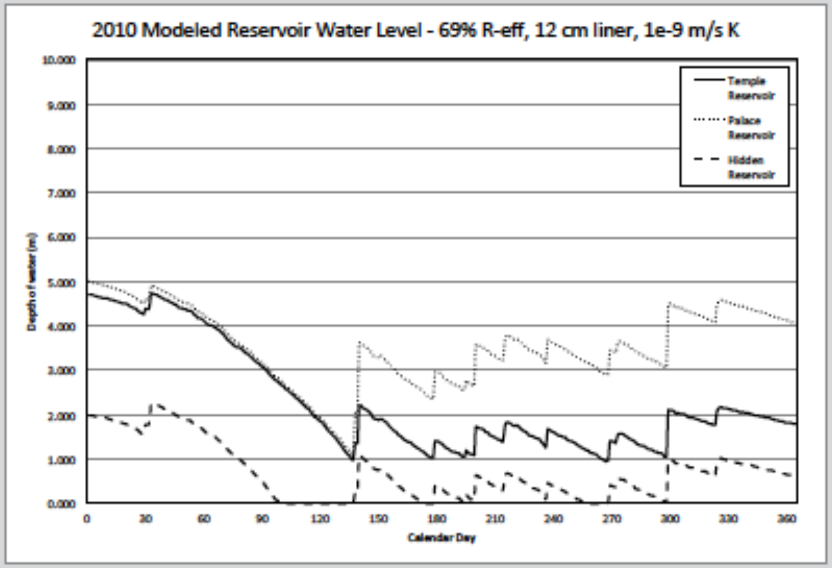


GSA 2012 – Florea – Results (La Nina Years)









The modeled water levels reveal an interesting trend for the available climate years, water levels in the reservoir end lower than they began.

This trend is even visible using thicker liners with lower conductivity and high values of runoff efficiency.

These trends are also visible in both El Nino (2007, 2009) years with lower precipitation and greater evaporation and La Nina (2008, 2010) years with greater precipitation and lower evaporation.

The results pose an interesting divergence from recent publications (e.g., *Scarborough et al, 2012; Gallopin, 1990*) that present data to support water-filled reservoirs with overflow utilized for irrigation.

Results in this model are more suggestive of hydrated wetlands with periods of desiccation during the dry season and highly variable water depths during the wet season.

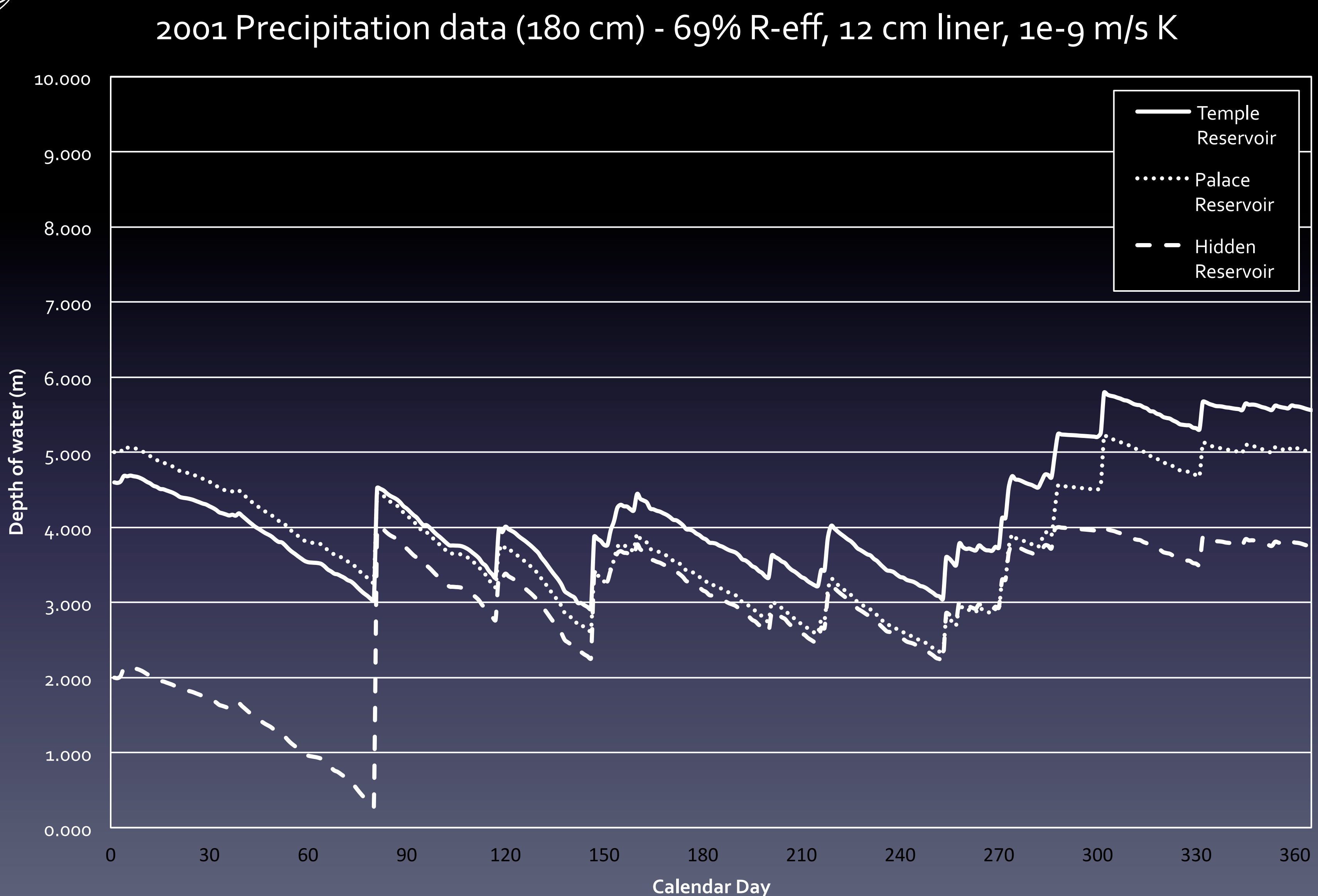
This second notion is more in line with *Jaccob (1995)* who argues that the reservoirs were in fact "marshy areas of perennial wetness."

If correct, this model suggests a few possible climate implications:

1) Annual precipitation may have been, on average, greater that modern available data during the Classic Maya period. If, for example, annual rainfall were to meet or exceed the level of the 2008 and 2010 La Nina years, water levels would remain elevated, particularly in the Temple and Palace Reservoirs. Significantly more precipitation could induce occasional overflow.

Interestingly *Gallopin (1990)* assumes an 150 cm/yr in his conceptual model.

GSA 2012 – Florea – Discussion



2) A modest reduction in annual precipitation (~20%) over an multi-year period, largely from a reduced number of tropical cyclones, could result in long-periods of limited reservoir hydration and therefore significant stress upon domestic and agricultural water use.

This second possibility has been long suspect in the collapse of the Classic Maya at Tikal and elsewhere with recent supporting data from stable isotopes (e.g., *Medina-Elizalde and Rohling, 2012*).

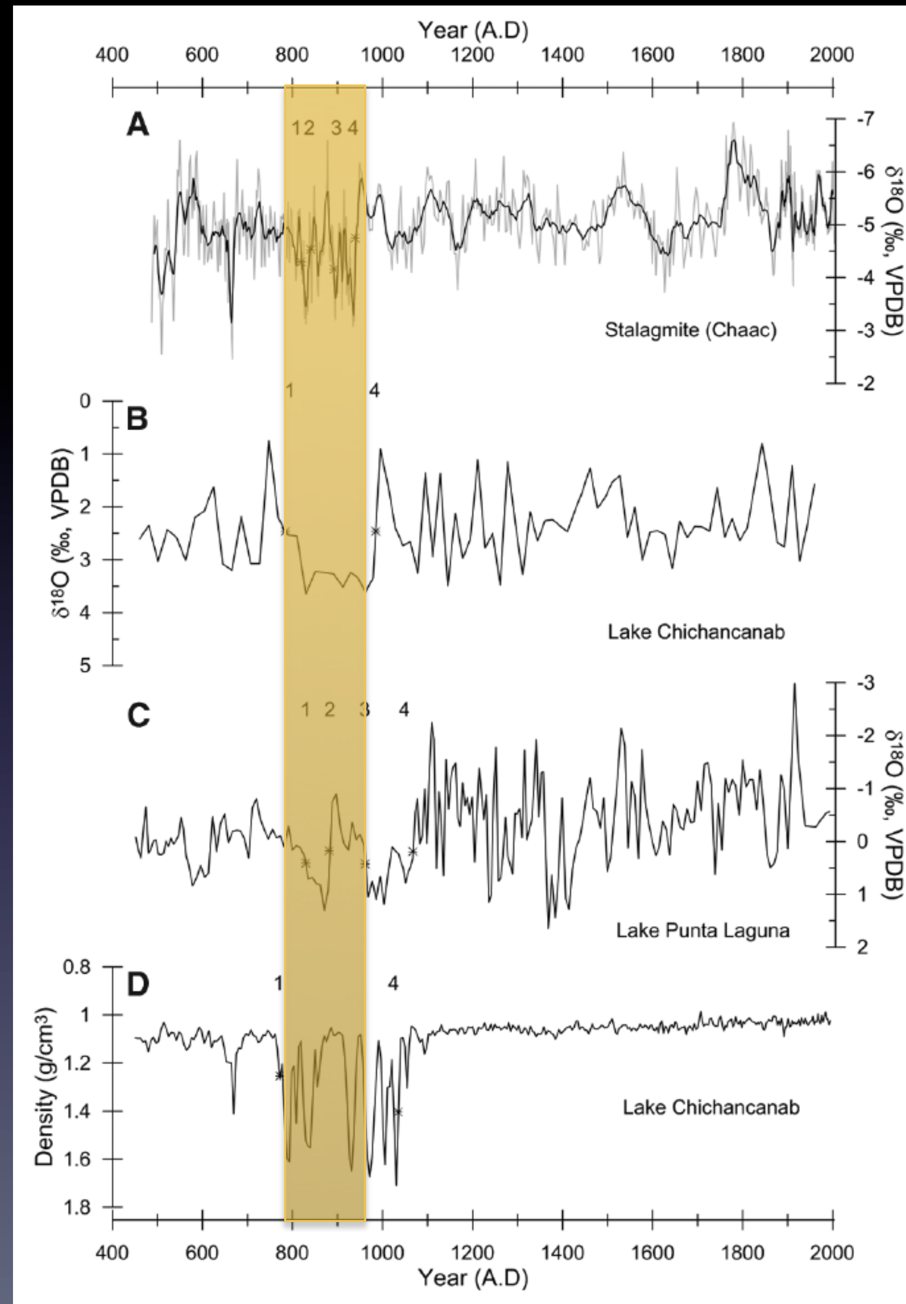
Science 335, 956 (2012); M. Medina-Elizalde and E.J. Rohling

A. Stalagmite Chaac $\delta^{18}O$ record

B. Lake Chichancanab *Pyrgophorus coronatus* $\delta^{18}O$ record

C. Lake Punta Laguna ostracod *Cytheridella ilosvayi* $\delta^{18}O$ Record

D. Lake Chichancanab sediment density record



Finally, these results imply the need for more detailed numerical modeling.

While an interesting exercise, we have reached the limits of a simple spreadsheet-based model.

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