General Guidelines for Calculating a Water Budget

Land and Water Management Division (LWMD)
March 2010

ISSUES:

A water budget is an accounting of all the water that flows into and out of a project area. This area can be a wetland, a lake, or any other point of interest. Development can alter the natural supply of water and severely impact an area, especially if there are nearby ponds or wetlands. A water budget is needed to determine the magnitude of these impacts and to evaluate possible mitigation actions.

DISCUSSION:

A water budget describes the various components of the hydrologic cycle. These components are shown in Figure 1. The water budget typically includes:

- Precipitation (P)
- Evaporation (E)
- Evapotranspiration (ET)
- Surface runoff (SRO)
- Groundwater flow (GF)

The water budget is expressed as an equation relating these components:

$$\Delta S = P - E - ET \pm SRO \pm GF \qquad (1)$$

where ΔS is the change in storage. For example, if the expression on the right-hand side of the equation is positive, storage will increase and the water level in the area of interest will rise. A positive change in storage is often termed a surplus, while a decrease in storage is termed a deficit. The change in storage is usually described with units of inches or feet.

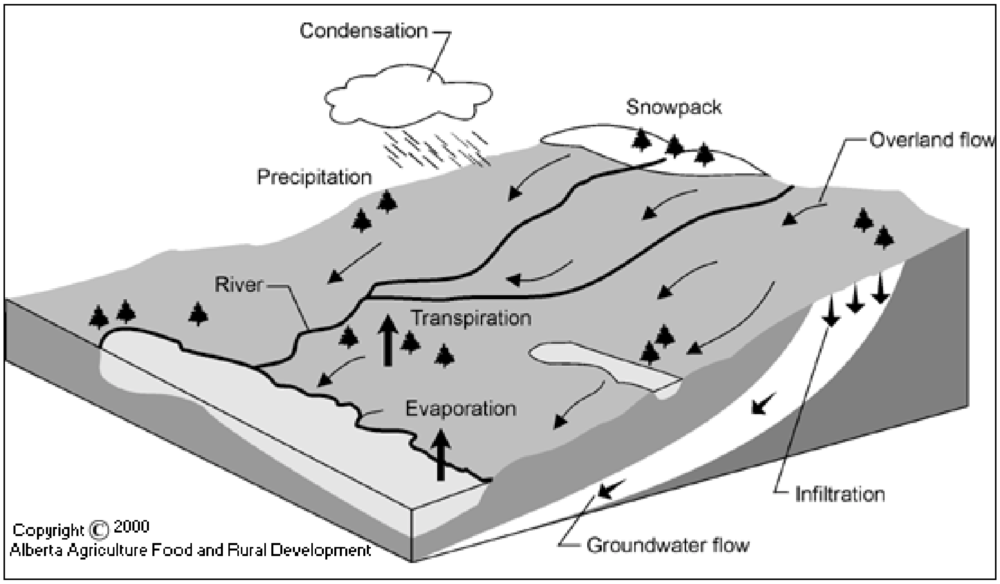

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Figure 1 - Components of the hydrologic cycle

In urban areas, the water budget equation may have an additional term that accounts for known point inflows or outflows. These point sources could be withdrawals for industrial uses, outflows from wastewater treatment plants, etc. The amount of water withdrawn or discharged by these point sources can usually be identified from their operating records.

The first three terms of the water budget equation, precipitation, evaporation, and evapotranspiration, are natural processes that are largely unaffected by development. However, changes in land use can significantly affect surface runoff and groundwater flow. For example, commercial development may intercept surface runoff that ran into a wetland and redirect it to a stormwater control basin. This stormwater basin may hold the water until it evaporates or release it to an outlet stream. In either case, the wetland is deprived of the surface runoff that was available before the development. Similarly, water supply wells can permanently lower groundwater levels and change flow directions.

A water budget is calculated for a specified period of time. Permanent projects may be evaluated using daily or monthly data, with the resulting net surplus or deficit is expressed as a seasonal or annual value. Short-term projects, such as lowering a reservoir for maintenance, may be evaluated using hourly or weekly data and express the results on a monthly or seasonal basis.

A water budget should be calculated for a range of conditions. Data from a year with an average amount of precipitation is used to describe long-term effects, but it may be necessary to evaluate ‘wet’ and ‘dry’ years for projects with sensitive, natural resources.

The most difficult part of computing the water budget is locating data that allows you to accurately estimate the net surplus or deficit. If the project depends primarily on surface runoff, you can identify years with normal, below normal, and above normal rainfall and use that information to determine the surface runoff under those three climate conditions. Rainfall data are readily available from the National Oceanic and Atmospheric Administration (NOAA) and other agencies. However, if the project area depends on groundwater flow, then you should ideally use groundwater flow data for a range of conditions. But groundwater flow data, if they exist at all, are usually only available for the time period when a permit application is being reviewed.

GUIDANCE/ACTION:

This guidance describes procedures to calculate the components of the water budget equation. Each component is discussed in detail and methods for determining that variable are listed.

This discussion also refers to the permit applicant. When referring to the applicant, we will mean that to also include the applicant’s consulting engineers or geologists.

Examples illustrating various situations are also included. Additional discussion and guidance is included in each example.

Precipitation

Precipitation is the primary water input to the hydrologic cycle and is evaluated for all water budget calculations. Precipitation data for a normal year should be used to evaluate the long-term impacts of a project. The precipitation data can be obtained from various NOAA publications. Average monthly and annual data for many locations throughout Michigan are readily available on the Michigan State University Climatology web site at http://climate.geo.msu.edu. Rainfall and climate data are also available from the National climate Data Center at http://www.ncdc.noaa.gov/oa/climate/climatedata.html. Daily rainfall data can also be obtained from LWMD's Hydrologic Studies Program staff.

The wettest or driest years on record do not always provide the most critical analysis. For example, the wettest year may have abundant rainfall in the spring and fall, but have a relatively dry summer. Alternately, what appears to be a normal or drier year may have most of the rainfall concentrated in the summer months. It may be more useful to examine the data and look specifically at the May-Sep rainfall to determine what years to analyze.

The precipitation data should be tabulated by month when evaluating the annual water budget. The analysis is facilitated by setting up the data in an Excel spreadsheet.

Evaporation

Evaporation, as distinguished from evapotranspiration, is the process by which liquid water from an open water surface is converted directly to water vapor. The National Weather Service (NWS) measures evaporation in an evaporation pan that is four feet in diameter, ten inches deep, and elevated approximately six inches above the ground to allow for air circulation around the entire pan. Evaporation data is currently collected at five weather stations across Michigan. Monthly pan evaporation data for the five stations in Michigan can be requested from the LWMD's Hydrologic Studies Program staff.

The evaporation measured in the pan is always greater than what would occur from a lake or pond. The measured evaporation must be multiplied by a coefficient to convert the observed values to an estimated value for lakes and ponds. That coefficient is usually around 0.7. Alternately, the NWS has published an atlas depicting estimated evaporation from a lake surface, on both an annual basis and for the growing season of May-October (1982). Since evaporation is a relatively minor concern during the colder months, the May-October map should be a reasonably good estimate of evaporation losses. This map is shown in Figure 2.

Although the map in Figure 2 may be adequate for most analyses, it may be necessary to distribute this evaporation over each of the six months. Based on recorded data at the evaporation stations in Michigan, the seasonal total can be distributed as follows:

Month	Percent of total May-October evaporation
May	18
June	20
July	23
August	18
September	12
October	9

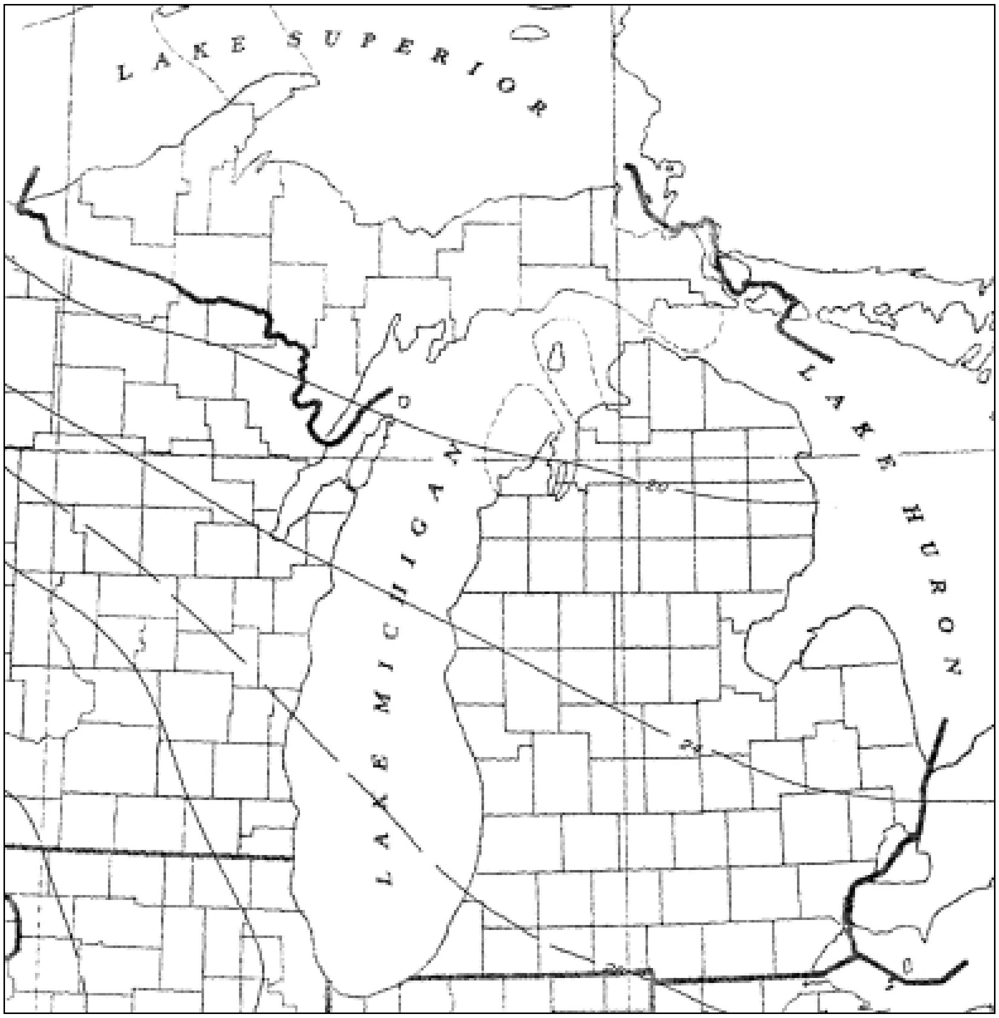

Figure 2 – May - October evaporation (in inches) from an open water surface

Evapotranspiration

Evapotranspiration is similar to evaporation, except that it applies to the combined effect of evaporation from the land surface and transpiration from growing plants. While evaporation is controlled exclusively by climatic factors, evapotranspiration also depends on the type of soil and plants. Evapotranspiration is most often determined by first computing the potential evapotranspiration (PET), which is the maximum amount of water loss if the plants have a constant supply of soil moisture.

Evapotranspiration is computed using the method devised by Thornthwaite and Mather (1957). This method computes the PET, then adjusts it to estimate the actual evapotranspiration. The method is contained in the program EVAP, which is available from the NWS Great Lakes Environmental Research Laboratory (1996).

The only required user input is precipitation, temperature, and latitude. This program is available at (http://www.michigan.gov/documents/deq/lwm-evap_313231_7.zip) or, for LWMD staff, in the S:\HYDRO\EVAP directory.

In some cases, you may need to evaluate evapotranspiration for a specific month. Real-time and historical evapotranspiration data for Michigan can be accessed through the MSU Agricultural Weather Office web site at www.agweather.geo.msu.edu.

In practice, both evaporation and evapotranspiration are tabulated for each month, or the growing season of May-October, then the higher value is used in the water budget. In most cases, evaporation is a more important factor when evaluating an excavated lake, while evapotranspiration may be more significant for wetland projects.

Surface Runoff

Surface runoff is not normally an important component in these calculations unless the pond or wetland is at the bottom of a slope that normally collects and holds surface runoff. This runoff may be needed to keep the wetland from going dry in the summer or at least provide enough water on a seasonal basis. Down-gradient wetlands can also be deprived of water if the surface runoff is diverted to a stormwater basin or collected by storm sewers and rerouted to another discharge point. Please note that these computations are not particularly difficult, but they are tedious and laborious. The surface runoff component should only be determined if the other factors yield an inconclusive answer.

Surface runoff is computed using the runoff curve number method (RCN), which was developed by the Soil Conservation Service in 1954. The combination of a hydrologic soil group and a land use and treatment class is a hydrologic soil-cover complex. Each combination is assigned a RCN, which is an index to its runoff potential. The RCNs for various combinations of soils and land use based on antecedent runoff condition II are shown in Table 1. If the antecedent runoff condition is the ARC I or III criterion, the RCN must be adjusted. The following adjustments show the equivalent RCN for ARC I and III.

$$RCN(I) = \frac{4.2 * RCN(II)}{10 - 0.058 * RCN(II)}$$

$$RCN(III) = \frac{23 * RCN(II)}{10 + 0.13 * RCN(II)}$$

Land use	Treatment or practice	Hydrologic condition	Hydrologic soil group			
			A	B	C	D
Fallow	Straight row		77	86	91	94
Row crops	Straight row	Poor	72	81	88	91
		Good	67	78	85	89
	Contoured	Poor	70	79	84	88
		Good	65	75	82	86
	Contoured and terraced	Poor	66	74	80	82
		Good	62	71	78	81
Small grain	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
	Contoured	Poor	63	74	82	85
		Good	61	73	81	84
	Contoured and terraced	Poor	61	72	79	82
		Good	59	70	78	81
Close-seeded legumes or rotation meadow	Straight row	Poor	66	77	85	89
		Good	58	72	81	85
	Contoured	Poor	64	75	83	85
		Good	55	69	78	83
	Contoured and terraced	Poor	63	73	80	83
		Good	51	67	76	80
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
		Fair	30	59	75	83
		Good	30	35	70	79
Meadow			30	58	71	78
Woods		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	30	55	70	77
Residential	⅛ acre		77	85	90	92
	¼ acre		61	75	83	87
	1/3 acre		57	72	81	86
	½ acre		54	70	80	85
	1 acre		51	68	79	84
Open spaces (parks, golf courses, cemeteries, etc.)	Good condition: Grass cover > 75% of area		39	61	74	80
	Fair condition: Grass cover 50-75% of area		49	69	79	84
Commercial or business area (85% impervious)			89	92	94	95
Industrial district (72% impervious)			81	88	91	93
Farmsteads			59	74	82	86
Paved areas (roads, drive-ways, parking lots, roofs)			98	98	98	98
Water surfaces (lakes, ponds, reservoirs, etc.)			100	100	100	100
Swamp	At least 1/3 is open water		85	85	85	85
	Vegetated		78	78	78	78

Table 1 - Runoff curve numbers for various land use/soils combinations (ARC-II)

Computing the surface runoff involves the following steps:

- Obtain daily precipitation data from a representative climate station within the same climate area as the wetland to determine the average, driest, and wettest years.
- Compute the average RCN of the area that drains to the wetland. Also compute the RCN for ARC I and III.
- For the computed RCNs, determine the rainfall required before runoff will occur. This is computed by I_a=0.2*((1000/RCN)-10). Do this for the RCN corresponding to all three ARCs.
- Examine the 5-day precipitation before each event in the years you are analyzing to determine the antecedent runoff condition.
- Using the appropriate RCN, compute the daily runoff for each day where the rainfall is great enough to produce runoff.

The daily data can be tabulated monthly and annually, as illustrated in Figure 3.

Although runoff can be grouped into monthly, seasonal, or annual values, the RCN method is only valid for individual events. Therefore, you generally need to apply I_a to each daily rainfall before computing any runoff. In some cases, a single storm may be continuous over two consecutive days and can be analyzed as one event.

Year	Runoff (in)										
	No. of Events	Month									Total runoff for year
		March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	
1990	3			0.54							0.87
1989	3			1.58							1.70
1988	0										0.00
1987	2			0.16							0.24
1986	0										0.00
1985	2							0.75			0.85
1984	1					0.25					0.25
1983	2				0.01						0.02
1982	3					0.25					0.29
1981	3							0.08			0.10
1980	4						0.19				0.24
1979	2						0.13				0.17
1978	2			0.33							0.37
1977	4			0.13							0.36
1976	0										0.00
1975	3				0.17						0.23
1974	1				0.3						0.30
1973	2	0.17									0.22
1972	3						0.14				0.16
1971	1				0.04						0.04
1970	2						0.12				0.13
1969	7				0.32						0.81
1968	2					0.39					0.45
1967	2				0.08						0.12
1966	1					0.05					0.05
1965	4								0.27		0.40
1964	1			0.16							0.16
1963	1				0.28						0.28
1962	0										0.00
1961	0										0.00
1960	1			0.27							0.27
1959	1								0.43		0.43
1958	2					0.05					0.07
1957	1				0.28						0.28
1956	1			0.03							0.03
1955	1		0.21								0.28
1954	3										0.00
1953	0										0.00
1952	0										0.00
1951	4			0.65							0.78

Figure 3 - Example of surface runoff computations

Groundwater flow

Groundwater flow can be an important consideration when evaluating applications for sand and gravel mining. The main concern of a mining operation that excavates a lake or pond is that it exposes the groundwater to the air, which increases losses through evaporation. For this case, the water budget is calculated using groundwater flow, precipitation, and evaporation. Surface runoff is usually a minor consideration for these projects.

In order to determine the groundwater flow component, one needs to have an estimate of the hydraulic conductivity (K) of the soil, or its ability to transmit water. The K can be estimated from well records and is usually determined by the applicant. The total groundwater flow into the project area also requires the cross sectional area and the slope (S_0) of the groundwater head contours. The saturated thickness of the aquifer (B) can usually be determined from well records. The width (W) of the aquifer that flows to the project area requires knowledge of the groundwater head contours. A good estimate of this value is the maximum width of the excavated lake, viewed looking "into" the direction of the groundwater flow. The slope of the groundwater head contours is determined from well records or other recorded water levels and should be calculated by the applicant.

The total groundwater flow (GF) into the excavated lake is then:

$$\text{GF (ft}^3\text{/day)} = \text{K (ft/day)} * \text{B (ft)} * \text{W (ft)} * S_0 \text{ (ft/ft)} \qquad (2)$$

This equation is known as Darcy's law. The results are typically converted to units of gallons per day (gpd).

If the change in storage shows there is a net deficit, the effect on water levels in nearby wetlands or ponds can be estimated by assuming this net deficit is equivalent to a pumping well located at the center of the lake. The net deficit in gpd is converted to gallons per minute (gpm) for these computations. A simple well hydraulics analysis based on the Theis equation is used to compute the drawdown. The calculations have been incorporated into an Excel spreadsheet, DRAWDOWN.XLS, located at (http://www.michigan.gov/documents/deq/lwm-evap_313231_7.zip) or, for LWMD staff, in the S:\HYDRO\EVAP directory.

EXAMPLES

Since most of the data are in units of acres, inches, and gallons, the following conversion factors may be useful:

Multiply	By	To obtain
acre-inch/day	27,156	gpd
feet^3/day	7.481	gpd
gpd	$6.94\text{x}10^{-4}$	gpm

Example 1

An applicant proposes a project to wet-mine for sand and gravel in southwest Ingham County. The excavation will create a 10-acre lake. A wetland is located 300 feet away from the proposed excavation. Estimate what effect the excavation will have on water levels in the wetland.

Since the project will not involve dewatering, the primary effect on the water budget is that the lake will expose the groundwater to the air, which will result in an increased loss from evaporation. We will assume the evapotranspiration and surface runoff components of the water budget are minor and will not be computed. We can also neglect the groundwater flow term since the natural flow through the area is not being changed. Therefore, equation 1 becomes:

$$\Delta S=P-E$$

Additional data supplied by the applicant show the following:

Saturated thickness of aquifer flowing into the excavation (B) =40 feet
Width of the proposed excavation perpendicular to the flow (W) =1200 feet
Slope of the groundwater table (S_0) =0.008 feet/foot
Hydraulic conductivity (K) =100 feet/day

To determine the evaporation, we use Figure 2 and find that the May through October evaporation in southwest Ingham County is approximately 25 inches. Since there are 184 days from May 1 through October 31, the daily evaporation is **0.136 in/day**.

Normal monthly precipitation data from the MSU Agricultural Weather Office web site at www.agweather.geo.msu.edu show that the May through October rainfall for this portion of Ingham County is approximately 18 inches, or an average of **0.098 inches/day**.

Then, using equation 1, ΔS is **-0.038 inches/day**. The negative sign indicates there is a net deficit. This net deficit of 0.038 inches/day from the 10-acre lake surface equals 0.38 acre-inches/day. These units are converted to **10,300 gpd** or **7 gallons per minute** (gpm).

We can calculate the normal rate of groundwater flow into the lake using equation 2 ($GF=K*B*W*S_0$). Substituting these data into equation 2 gives us a groundwater flow, GF, of 38,400 ft^3/day or **287,000 gpd**.

Based on the normal groundwater inflow to the excavation, the net evaporation deficit represents a seasonal, groundwater flow rate reduction of 2 percent. DRAWDOWN.XLS is used to determine what effect this deficit will have on water levels in the wetland. Data needed for the calculations are the transmissivity (T) and storativity (S) of the aquifer, the distance from the well to the point of interest, the pumping rate, and the number of days the well is pumping.

The transmissivity is equal to the hydraulic conductivity times the saturated thickness of the aquifer (T=K*B). The units are ft^2/day. For our example, T equals 4000 ft^2/day for a K of 100 feet/day.

The storativity should be determined by the applicant. In the absence of field data, the storativity of an unconfined aquifer usually ranges from 0.01 - 0.3, while a confined aquifer ranges from 0.005 - 0.00005. Storativity is dimensionless, so there are no units. For our example, we will assume S = 0.01.

Since we are evaluating the net evaporation deficit from the May through October time period, we will use 184 days for the duration of the pumping. The distance from the edge of the lake to the wetland is 300 feet. The distance from the edge of the lake to the center (where we assume the pumping well would be located) is 700 ft. Thus, the total distance from the well to the wetland is 1000 feet.

The input data used in DRAWDOWN.XLS is

T=4000 ft^2/day (for K=100 feet/day)
S=0.01
Well pumping rate=7 gpm
Time=184 days
Distance=1000 feet
Distance increment=100 feet

Output shows the drawdown at the wetland is 0.14 feet. Therefore, the net effect of the excavation will be to lower the water level in the wetland about 0.1 feet.

Example 2

Given the same data in example 1, assume that the applicant wishes to dewater the excavation to mine the sand and gravel. How will this affect water levels in the wetland?

We already noted that the normal groundwater flow into the excavation will be 287,000 gpd. There will be no evaporation, since there will be no open water surface. However, we still need to account for the precipitation that falls directly into the excavation.

The May through October precipitation of 0.098 inches/day is equal to 27,000 gpd. Thus, the total amount of water that needs to be dewatered is 314,000 gpd or 218 gpm.

DRAWDOWN.XLS is run with these data and shows a drawdown of 4.3 feet. Thus, dewatering the excavation to mine the sand and gravel will lower the wetland water level approximately 4-5 feet.

Example 3

A proposed subdivision plans to collect stormwater runoff and divert it into detention basins. However, diverting this runoff will eliminate the surface runoff that now flows into a wetland on the 'downhill' side of the development. We need to determine how this development will impact the wetland.

The only change to the existing condition is that surface runoff to the wetland is being reduced. We don't really need to evaluate the other terms in the water budget, but can assume that the water supply, including the surface runoff, is adequate or else there wouldn't be a wetland in the first place. So equation 1 reduces to:

$$\Delta S = -SRO$$

The surface runoff term is negative since SRO is being reduced.

Example 4

Assume that the wetland in example 3 didn't exist but the applicant was proposing to create a new wetland as part of a mitigation plan. We need to determine if there will be a sufficient supply of water to maintain the functions of the new wetland.

We will have the same surface runoff deficit as determined in example 3. However, in this case, we will need to evaluate the rest of the terms in equation 1. We would expect that evapotranspiration will exceed precipitation and increase the net deficit, and that groundwater flow will be needed to make up that deficit and make the wetland viable.

Evapotranspiration is computed using program EVAP. The input data includes the latitude of the site (42.5°), the monthly average temperature (°C) and precipitation (mm), and the soil moisture handling capacity (assumed to be 250 mm for this site). The input data and computed evapotranspiration are shown in the following table. Note that program EVAP works with metric units and you need to convert the ET into inches.

Month	Precipitation		Temperature (°C)	Evapotranspiration (ET)	
	(mm)	(inch)		(mm)	(inch)
May	73.3	2.9	14.17	82.30	3.3
June	92.7	3.7	19.44	117.70	4.7
July	72.8	2.9	21.50	119.80	4.8
August	81.1	3.2	20.56	106.10	4.2
September	69.8	2.8	16.67	75.80	3.0
October	58.0	2.3	10.61	42.75	1.7

The total evapotranspiration is 23.7 inches and the total precipitation over the same time is 22.8 inches.

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