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ECOSYSTEM STUDIES AT CEDAR CREEK NATURAL HISTORY AREA, III: WATER USE STUDIES

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Previous articles in this series (Lawrence *et al.* 1957-58, 1960) have dealt with the nature of ecosystems, history of the ecosystem analysis approach, and some of the objectives and the methods that have been used at the Cedar Creek Natural History Area of the University of Minnesota and the Minnesota Academy of Science. The area, which was acquired in large part through a generous grant from the Fleischmann Foundation, is located in Anoka and Isanti Counties in east central Minnesota. The work has been generously supported by the Hill Family Foundation since the early summer of 1957.

One main objective has been to learn what becomes of the solar energy striking the landscape. It has been estimated from studies elsewhere that a rather large portion, probably over half of the energy which strikes a given level area, is expended in evaporation from non-living surfaces of open water and moist soil, and in transpiration from living plant surfaces. The combined vaporization is called evapotranspiration. The Cedar Creek area is especially well suited for studying these water losses, or "uses" as we shall consider them here, because such a large variety of surfaces occur in close proximity to one another, and because water surface is exposed in ponds and the water table is usually at the surface or within a few inches of the surface in willow, alder, and tamarack swamps.

There are two methods by which rates of water loss from landscape surfaces can be estimated. One method involves measurements of vertical gradients of atmospheric moisture, as well as of horizontal and vertical flow rates. We have not yet attempted this method which requires complex and costly instrumentation. The other method, which is more direct, involves the establishment of watertight tanks to which liquid water can be added in measured amounts to replace vaporized losses. The present report describes the results of studies based on this second method.

In the late spring of 1958 three cylindrical galvanized sheet-steel cattle tanks 45 inches in diameter and 2 feet deep, with vertically pleated walls, purchased from Sears, Roebuck and Co., were installed in a marshy area about 470 yards east northeast of the laboratory by Lawrence, Bray, and Pearson. The landscape area enclosed within each tank was 11.045 sq. ft., or 25.35×10^{-5} acre. One was placed in an open water pond about four times as large as the tank, one in a sedge marsh, and one in a cat-tail marsh, all in an area no more than a hundred yards in diameter. The tanks were sunk into the muck until the top rim was within 6 inches of the water surface. Those in the sedge and cat-tail communities were filled with soil and vegetation to the same levels as outside. The task was difficult in the cat-tail stand because of ice at shallow depth so that installation could not be completed until two weeks later. Throughout the summer measured amouns of water were added by Pearson, Bray, and Rogosin at approximately 10-day intervals to bring the level inside the tanks up to that of the water table outside. Water level was adjusted, whenever possible, by surface water collected from adjacent marsh. In dry periods water was carried from the deep laboratory well which taps the Galesville Sandstone. This method provided very natural conditions with respect to water table but, because the level of the water table outside sometimes fluctuated during the interval and natural additions by precipitation occurred occasionally, the periodic additions, even when corrected for precipitation, do not give precisely the amount vaporized from the tanks during the short periods. However, since the water table at the end of the season was approximately the same as at the beginning, losses for the whole season do give a fair measure of water vaporized from the tanks. The losses including vaporized precipitation from June 5 to October 3 are presented in Table 1.

TABLE 1. Total water use in inches, June 7 to October 3, 1958. Values are sums of manual additions and precipitation measured in nearby rain gauges.

	June		July		August					Sept.	Oct.	Seasonal Totals	Daily Means	Percent of Open Water Tank
Dates	17	28	12	20	2	8	14	20	25	19	3			
Open water	2.67	.96	2.15	.80	1.37	1.36	1.17	.32	1.08	3.84	.20	15.92	.126	100%
Sedge	1.08	.96	2.47	1.12	1.69	1.68	1.17	.95	1.08	4.16	1.47	17.83	.142	112%
Cat-tail	.76	.64	2.15	1.12	1.69	3.27	2.44	.95	1.08	4.16	1.15	19.41	.154	122%
Rainfall	.76	.64	2.15	.80	1.37	1.04	.53	..	1.08	3.84	.20	12.41	.098	...

Total losses for the season are: 15.92 inches from the open water tank, 17.83 inches from the sedge tank, and 19.41 inches from the cat-tail tank. The rainfall during this period amounted to 12.41 inches; it was measured this first season in a series of Cenco field precipitation gauges, with orifice 3 inches in diameter, sunk partly into the soil of a grass-covered abandoned field about 100 yards from the tanks. As based on these measurements, evapotranspiration appears to have exceeded the precipitation by 3.51 inches from the open water tank, by 5.42 inches from the sedges, and by 7.00 inches from the cat-tails. Comparative water losses from the vegetated tanks based on the open water tank as 100% are: sedge 112%, and cat-tail 122%.

It would be misleading to give the impression that these values possess a high degree of accuracy and complete applicability to natural conditions, because they are influenced by several unknowns related to effects of the tank wall on evaporation, and to different amounts of precipitation entering the tanks than can be measured by rain gauges. The tank wall extended about 4 to 6 inches above the water surface and this distance fluctuated both inside and outside the tanks. The tank wall quite surely influenced wind movement across the vaporizing surfaces. The tank wall would be expected to absorb radiant energy strongly by day, warming the surface water, but it also would give off heat rapidly on clear nights, cooling the surface water. These effects would presumably influence the evaporation rate only from the open water tank, perhaps resulting in evaporation somewhat less than the evaporation from a smooth surface of a natural pond of similar size. However since the natural ponds of the area are surrounded by sedge vegetation even taller than the tank wall, the wind-reducing effect of the wall should not have been as unnatural as one might expect. Vegetation surfaces in and around the other tanks extended far above the rims, largely hiding them from view, so that wall effects should be negligible for them.

Still unknown are the amounts of precipitation intercepted by the vegetation which would tend to keep some of the raindrops up on the leaves, whence some of the water would evaporate and some would be absorbed into the plant. Also unknown is the amount of external flow along stems and leaves which could bring more rain into the tank than would be estimated from the catch of an ordinary rain gauge. This effect would be especially important when the rain is driven laterally by wind. Since some of these influences oppose and others reinforce one another, the use of a single precipitation value, derived from a standard rain gauge, for computing natural additions to all the tanks alike may not be as objectionable as one might suspect. Comparative losses during a two week drought in 1960, to be presented later, will avoid rainfall difficulties and allow clearer interpretation.

It should be pointed out here that we had expected these thin-walled tanks to be split by freezing if they were left undrained through the winter, but when spring of 1959 arrived, water stood higher inside the tanks than outside, indicating that they had not been ruptured. The tanks passed through a second winter unruptured also. Perhaps this unexpected freedom from freezing damage has resulted because we made sure that levels inside and outside the tanks were the same at time of freezeup, so that outward pressure exerted on the tank walls by ice was counterbalanced by inward pressure of ice freezing on the outside. The vertical pleating of the walls of these first tanks may have been important in preventing rupture; the pleating has become notably less over the three years that have now elapsed.

During the first winter the cat-tails in the one tank died, perhaps by freezing, and marsh grasses and sedges replaced them by natural processes during the summer of 1959, so that the vegetation within two of the tanks became superficially alike although their surroundings remained very different.

During the 1959 season manual additions were made by Ovington, Heitkamp and Bonde at intervals of three to six weeks. Levels inside the tanks fell in some instances far below that of the ground water table, and this of course was less natural. But in this season additions were always made until the level in the tank reached a marked zero point so that losses for each period could be truly comparable.

TABLE 2. Total water use in inches, June 1 to October 5, 1959. Values are sums of manual additions and precipitation measured in a nearby rain gauge.

Dates	June 1	July 15	Aug. 4	Sept. 8	Oct. 5	Seasonal Totals	Daily Means	Percent of open Water Tank
Open water	—	5.21	4.86	6.20	1.44	17.71	0.141	100%
Sedge	—	9.06	8.06	6.78	2.44	26.34	0.209	149%
Formerly Cat-tail, now marsh grass and sedge	—	5.94	5.88	6.93	2.69	21.44	0.170	121%
Rainfall	—	4.05	2.97	6.20	5.44	18.66	0.149	

The values of manual replacements and of measured precipitation for the 1959 season are presented in Table 2. It will be noted that seasonal losses from June 1 to October 5 were: 17.71 inches from the open water tank, 26.34 inches from the sedge tank, and 21.44 inches from the former cat-tail tank, now marsh grass and sedge. The rainfall during this period amounted to 18.66 inches. Thus loss from the open water tank appears to have been 0.95 inches less than precipitation, loss from the sedge tank exceeded precipitation by 7.68 inches, and loss from the marsh grass and sedge tank surrounded by cat-tails (formerly the cat-tail tank) exceeded precipitation by 2.78 inches. Water losses from the vegetated tanks compared to the open water tank as 100% are: sedge 149%, and marsh grass and sedge (formerly cat-tail) 121%.

We wish to take the opportunity here to point out an error in the second article of this series (Lawrence *et al.* 1960) in which it was stated that the sedge tank had vaporized 3.5 times, and the marsh grasses and sedges in the original cat-tail tank a little less than twice as much as the open water tank. These stated relationships were incorrect because the values were not corrected for precipitation.

In mid-December, 1959, four additional cylindrical tanks, 4 feet in diameter and 2 feet deep, were purchased with National Science Foundation funds, from the Hudson Equipment Company of Minneapolis; these tanks had smooth walls without pleats. A new technique was attempted by Heitkamp, Neumann and Bonde for transplanting vegetation into the tanks. Four woody plants, two shrubs and two trees, were selected in advance on the basis of symmetry and size so that their crown-cover, projected vertically downward, would lie just within the limits of the tanks. Thus any measured loss from the tanks could be applied rather validly to units of area of landscape, in this case 12.566 sq. ft. or 28.85×10^{-5} acre. The two shrubs chosen, a swamp willow five feet tall, and an alder six feet tall, were growing in a broad transition zone from marsh to swamp. The two trees, a tamarack 10 feet tall and a paper birch 15 feet tall were in a tamarack swamp which had been thinned by wind storms a few years before. It was natural for the individual trees to occur there in scattered positions rather isolated from one another. The area extends as much as 240 yards from the previously installed tanks, to a distance approximately 710 yards east northeast from the laboratory. All the plants were growng on organic substrata; they were transplanted into the new tanks in the same places where they had grown naturally. The method consisted of cutting a circle, slightly smaller than the tank, around each shrub or tree with a chain saw, through the surface ten-inch layer of ice which prevailed at the time, prying up one edge with steel fence posts, and sliding out the frozen mass. Because the soil consisted of organic material, peat and muck, no damage to the saw occurred. The tank, previously coated inside and out with asphalt roof paint, was then inserted into the enlarged hole and the ice cylinder containing the relatively undisturbed roots of the plant was slid into the tank on top of some unfrozen peat which had been removed from the hole and placed in the tank. The original compass orientation of the disc was maintained. The living root systems are all very shallow in swamps and marshes, because dissolved oxygen is available only near the surface; they all lay within the uppermost ten inch layer which was frozen at that time. Some of the outer ends of the roots were severed, but the birch tree was the only one of the four which seemed to be unfavorably affected by the transplanting. The record for the birch tank is therefore omitted. These four new tanks all survived that winter without rupture in spite of the fact that the walls of the new tanks were not of pleated construction.

A narrow board walk supported on sections of used cedar telephone and power poles was constructed in the spring of 1960 for access to the tanks. Measurements of water use were made weekly from the time of spring thaw on May 2 until fall freeze on November 9. Water was added by half-gallon increments until it rose to a previously designated zero point. Or the water level was brought down to the zero mark and the excess was measured if rainfall had caused it to rise above the mark.

Precipitation was measured by Alvar Peterson in the 1959 and 1960 seasons with a standard 8-inch Weather Bureau gauge. Measurements were made to the nearest 0.01 inch after each storm and at intervals within heavy storms. The orifice was 30 inches above the ground surface in an open field of grasses averaging 20 inches tall. The gauge was about 100 yards northeast of the laboratory; the evaporation tanks lie 370 to 600 yards east northeast of the rain gauge.

In order to interpret the water use data and relate them to precipitation, we have converted all measurements in gallons to inches of depth. The conversion values used are: 6.88 gallons per inch in the 45-inch diameter tanks, and 7.83 gallons per inch in the 48-inch diameter tanks.

In the 1960 season, automatic replacement of loss in the open water tank was provided by a calibrated water reservoir consisting of a white 55-gallon steel drum, factory lined with plastic resin rustproofing, and fitted with an exterior glass burette for easy observation of the internal water level. The reservoir was connected to a float valve in the evaporation tank by a plastic hose submerged in the peat. This worked well and it had been intended to provide similar automatic replenishment to the vegetation tanks but because the water level in some tanks was at or below the soil surface it was believed that the float valves would become too easily clogged in these. In this year well water was used for replacement after July 18th.

When the water level in the tanks was at or below the soil surface we experienced difficulty in judging when enough water had been added to bring the water level to the reference mark and, following rain, in removing excess water. Ways of surmounting these difficulties are under consideration.

The results of the 1960 season appear in Table 3. Because the tanks were serviced rather regularly, usually each Monday, from early May to early November, there is much greater detail available in the record than for previous years. The tanks were tended this year by Bonde. The general trend of increased use of water in the summer months followed by reduced use toward autumn is seen in all the records although the peaks were not all in the same month. The midsummer trends are most easily seen in the August record where the daily average loss in inches from the open water tank was .100, from the sedge tank .122, from the former cat-tail tank, now marsh grass and sedge .120, from the willow tank .167, from the alder tank .267, and from the tamarack .102. The alder tank is seen to have lost 2.67 times as much as the open water tank, and the tamarack only 1.02 times as much as the water tank. The small loss from the tamarack as compared with the alder is probably related to the high resistance to flow of sap through the short narrow gymnosperm tracheids as contrasted with the low resistance to flow through the much longer, wider angiosperm vessels. Gymnosperms have long been known to be much more conservative of water than angiosperms.

This season was particularly interesting because a three week drought occurred in late July and the first half of August in which only .03 inch of rain fell. The record for this period is presented in Table 4 so that evapotranspiration differences essentially unaffected by precipitation can be appraised. The most extreme differences occurred in the first week of the drought in which, as compared with the open water tank, the sedge tank vaporized almost 3 times as much, the former cat-tail about twice, the willow about 2.5 times, the alder 5 times, and the tamarack about 1.5 times.

For the whole drought period these relatons were approximately 1.6 for the sedge, 1.3 for the former cat-tail, 1.9 for the willow, 2.9 for the alder, and 0.9 for the tamarack.

The greater loss of water from the vegetated tanks as compared with the open water tanks is all the more notable in view of the reduction in wind velocity and increase in humidity that we could feel as we walked from the position of the open water tank to the vicinity of the alder and tamarack on hot calm days.

In the summer of 1961, following the oral presentation of this paper, evaporimeter stations were established by Ives, Bonde, and Sanger within 15 feet of the center of three of the tanks: the open

TABLE 3. Average daily and total seasonal water use in inches, May 2 to Nov. 8, 1960. Use in the full leaf period is presented separately at the right. Values include manual additions and precipitation minus removals.

Periods	Average Daily Losses in Inches								
	May 5/2-5/31	June 6/1-6/28	July 6/29-7/26	Aug. 7/27-8/30	Sept. 8/31-9/26	Oct. 9/27-10/31	Nov. 11/1-11/8	Total Season 5/2-11/8	Full Leaf Period 6/1-10/3
Open water	.072	.121	.137	.100	.081	.058	.012	17.21	13.46
Sedge	.098	.132	.155	.112	.068	.042	.012	18.22	14.22
Formerly Cat-tail, now marsh grass and sedge	.083	.155	.129	.120	.065	.046	.012	18.08	14.36
Willow	.105	.168	.153	.167	.099	.040	.013	22.03	18.05
Alder	.103	.203	.251	.267	.149	.049	.021	30.98	26.81
Tamarack	.094	.148	.135	.102	.076	.029	.013	17.33	13.92
Rainfall	.142	.153	.062	.131	.115	.023	.021	18.74	13.86

TABLE 4. Total water use in inches, for the 21-day drought, July 25 to August 15, 1960. Values include manual additions and the 0.03 inch precipitation measured in a nearby rain gauge.

Dates	July 25	August 1	8	15	Three-week Totals	Daily Means	Percent of Open Water Tank
Open water	—	0.45	0.89	1.02	2.36	0.112	100%
Sedge	—	1.32	1.18	1.61	3.66	0.174	156%
Formerly Cat-tail now marsh grass and sedge	—	0.95	1.04	1.16	3.15	0.150	134%
Willow	—	1.16	1.42	1.15	3.73	0.178	159%
Alder	—	2.24	2.32	2.23	6.79	0.323	288%
Tamarack	—	0.65	0.66	0.89	2.20	0.105	93%
Rainfall	—	0.01	0.02	0	0.03	0.0014	

water, the willow, and the alder, in order to find out more accurately how much the degree of atmospheric thirst diminished in the transition from marsh to swamp. The instruments used were calibrated Livingston black porous porcelain spherical atometers (Livingston 1935), which integrate the influence of wind, vapor pressure deficit and sunshine on evaporation. They were supported in a vertical series of three at each station, at about 8 inches, 60 inches, and 114 inches above the water or muck surface. Though the data are rather fragmentary, they show that the amount of distilled water vaporized from the middle instrument at the five foot level is very nearly equal to the average values for all three levels. For the 35 days of observation in six intervals between July 6 and Sept. 19, the average daily vaporized water losses from these middle height instruments averaged 35 g at the open water tank, 33 g at the willow tank, and 22 g at the alder tank. For the last 12 day period of operation, Sept. 7 to 19, the only days when the record is complete, average daily water losses from instruments at the open water tank were: upper 30.5 g, middle 28.8 g, and bottom 22.9 g. Considering each of these as 100% for their respective levels, atmometer losses at the willow were 104%, 96%, 78%, and at the alder were 59%, 52%, and 44%. Thus it is seen that evaporativity values declined markedly from the open water site eastward toward the alder site, especially at the middle and lower heights above the substratum where the vaporizing surfaces in the evapotranspirimeter tanks are located. Thus the high rate of loss of water from the alder tank in spite of evaporativity pressures only 59% to 44% as large emphasizes the potentially greater use of water by alder swamp vegetation.

Although the alder vegetation seems extraordinarily extravagant of water, it is still very important in the economy of nature because these shrubs fix atmospheric nitrogen in nodules on their roots so that their leaves can be as high in nitrogenous substances as are the leaves of alfalfa; about 3% of their dry weight is nitrogen. Thus there accumulates in the soil beneath the alders, a large reservoir of fixed nitrogen available for use by the trees which will form the later forest stages in the swamp succession (Lawrence 1958).

The greater use of soil water by living plants than by open water surfaces is well known to ecologists and hydrologists, but to few other people. One often hears conservationists discussing vegetation, and particularly forests, as conservers of moisture. But it has been shown that the plant cover does vaporize even more water than does an open pond because of increased surface area and increased absorption of solar energy as compared with flat open water. Although the general public is not yet concerned about water shortages in Minnesota, the time may not be far off when our state will be conserving its water resources much more carefully. When that day comes, we shall need to consider the relative water use of various kinds of vegetation.

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