CONSUMPTIVE USE OF GROUND WATER BY PHREATOPHYTES AND HYDROPHYTES

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In many parts of the southwest the ground water supply is exceedingly limited, and the demands for water, already great, are constantly increasing through pumping for irrigation, industrial and domestic purposes. When making an inventory of the water resources of a river basin, water consumed by phreatophytes (ground-water vegetation) such as cottonwoods, salt cedar (tamarisk), willows and salt grass growing in areas of high water-table and along streams becomes of increasing importance as greater land areas are irrigated, especially during periods of drought. Through the process of transpiration, these plants discharge and waste large quantities of ground water into the atmosphere.

Consumptive use (evapotranspiration) involves problems of water supply, both surface and underground, and watershed management, as well as those of the management of, and general economics of, irrigation, and multiple-purpose projects. Data on the use of water by vegetative cover essential in planning government and private irrigation and water supply projects. The consumptive-use requirement for water has become an important factor in the arbitration of controversies regarding major stream systems, such as the Rio Grande (2) in the United States and Mexico, in which the welfare of the people of valleys, cities, states and even nations is involved.

Research studies show that the rates of consumptive use (evapotranspiration) by phreatophytes and hydrophytes are much greater than the use of water by most irrigated crops. This paper describes and presents the results of studies and measurements of the use of ground water by phreatophytes and hydrophytes in arid and semi-arid areas of the United States, and describes a method of determining rates of water consumption in areas where no measurements except climatological data are available.

Introduction

Adaption of plants to natural conditions has distributed vegetation in more or less dominant communities throughout the world. These may be classified as: (a) Xerophytes, plants that have adapted themselves to deficient and irregular water supplies; (b) Mesophytes grow in habitats that usually have neither excess nor deficiency of water;

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(c) Hydrophytes live wholly or partly submerged in water or with roots in saturated soil that is intermittently submerged; and (d) Phreatophytes, plants that habitually grow where they can send their roots down to the water table or the capillary fringe immediately overlying the water table.

The term "phreatophyte" was first used by the late Dr. C. E. Meinzer in the early twenties (9). The word is derived from two Greek words meaning well plant. In proposing this name, Meinzer indicated that it would overlap some of the other groups such as hydrophytes.

The term "consumptive use" has been used for some 50 years by irrigation engineers in the United States. It is considered synonymous with the term "evapotranspiration" and is defined as the quantity of water evaporated and transpired from an area. It may be expressed as a rate, depth in inches or depth in feet (ac. ft. per Ac.).

In determining the available water supply of a river drainage basin for irrigation and other purposes, ground water consumed by phreatophytes such as tamarisk (salt cedar); cottonwoods, willows, and salt grass and by hydrophytes such as tules, bull-rushes and sedges, should be given careful consideration before new multiple-purpose projects are authorized. The value of data on consumptive use by these plants is recognized by administrators and engineers in regions where water rights are in dispute, or where internation and interstate water supply and water use are not in balance (2, 4).

The moisture requirements of water-loving native (natural) vegetation are usually satisfied before water becomes available for irrigation and other purposes. Measurements of evapotranspiration indicate that water-loving native vegetation uses from 50 to 100 percent more water than most crop plants. Tules and salt cedar growing in irrigation canals and drainage ditches and on their banks are exposed in narrow strips to sun and wind so that their consumption of water is unusually high (1, 15). The United States Geological Survey (12) has estimated that the total area of phreatophytes is over 15 million acres in the 17 western states, and that the total use of water by these plants is about 25 million acre-feet annually. With the exception of salt cedar, most of the phreatophytes growing in Western United States are indigenous to this country. Salt cedar was introduced into the United States from Mediterranean region about 1900. These include some 15 varieties which are spreading rapidly.

This paper presents data on measured consumptive use of water by phreatophytes and hydrophytes and describes a method of determining rates of water consumption in areas where no measurements except climatological data are available.

Conditions Affecting Water Use

Many factors operate singly or in combination to influence, the amount of water consumed by plants. The effects of these factors are not necessarily constant but may fluctuate from year to year as well as from place to place. The effect of sunshine and heat in stimulating transpiration was studied as early as 1691 by European investigators. Measurements of transpiration of various kinds of plants indicate a close correlation between transpiration, evaporation, temperature, solar radiation and humidity.

The three primary factors that affect the annual rate of water by phreatophytes are: (a) depth of water table, (b) climatic conditions and (c) density of plant growth. Usually, the shallower the water table, the higher the rate of use. For some species, the depth to ground water is the controlling factor on their occurrence and growth. For instance, salt grass commonly grows only where the depth of the water does not exceed 7 feet, while mesquite is a deep-rooted plant that has been known to send its roots 50 feet or more in search of water (15). In soils of fine texture, the height of the capillary fringe is greater than in soils of coarse texture. Thus in coarse sandy soil the capillary fringe may not extend more than one foot above the water table, while in a clay soil it may supply moisture to 7 or more feet above the water table for plant growth. Measurements by the writer indicate that most of ground-water discharge by phreatophytes occurs in areas where the depth to water is less than 15 feet. Climatic conditions control the occurrence and growth of some species, whereas others are relatively unaffected by climate. The effect of climate on the growth and occurrence of salt cedar is very noticeable. The use of water by phreatophytes is influenced by temperature, daytime hours, length of growing season, precipitation and humidity. The effect of density of growth on use of water by salt cedar, cottonwood and willows was demonstrated in the course of intensive studies in Safford Valley, Arizona, in 1943-44 (8). It was found that the water use varied directly with the volume density.

Use of Water Measurements

Evapotranspiration losses by phreatophytes and hydrophytes growing in areas on high-water table have been measured by means of tanks, lysimeters, inflow-outflow, ground-water fluctuations and other methods by Federal and State agencies (1, 2, 8). At various times during the past 30 years the writer has measured rates of consumptive use in California, Colorado, New Mexico and Texas (1, 2, 4). The results of some of these measurements and those made by other investigators are shown in Tables 1 and 2.

Table 1-Examples of measured monthly consumptive use of water by natural vegetation growing in lysimeters with high-water table in Western United States (Compiled by Harry F. Blaney)

Location	Type of vegetation	Apr	May	June	July	Aug	Sept	Oct	Authority
		Consumptive Use of Water, inches							
CALIFORNIA									
Bonsall	Cottonwood b/	5.2	8.5	7.5	9.6	9.4	7.2	-	Muckel and
"	" a/	7.0	10.5	11.9	16.5	14.2	9.8	-	Blaney
" c/	Tules	4.6	7.1	7.5	8.6	7.4	5.7	4.7	Ditto
Victorville d/	"	7.5	11.6	12.2	14.6	12.0	10.6	5.7	"
Santa Ana	Saltgrass b/	3.6	3.7	5.8	7.6	6.1	4.5	3.0	Blaney and
" "	" e/	.7	.7	1.3	2.7	3.1	1.8	1.7	Young
" "	Willows	2.3	3.5	3.8	4.2	4.8	4.2	2.9	Ditto
" "	Wire rush f/	7.8	8.6	10.3	13.7	12.7	10.7	8.2	"
San Bernadino	Bermuda grass a/	2.0	2.1	4.5	5.4	3.9	3.1	.9	"
" "	" " g/	2.7	2.7	5.4	6.4	5.3	3.4	1.3	"
" "	Tules	5.4	4.6	6.0	6.8	5.8	5.1	4.9	"
COLORADO									
Alamosa	Tules	-	-	11.4	11.6	8.3	4.1	2.0	Blaney
"	Meadow Grass	-	-	6.5	8.3	7.8	5.8	1.2	"
Garnett	Saltgrass e/	1.7	3.0	6.2	6.7	5.9	3.5	1.6	"
NEW MEXICO									
Albuquerque	Tules	5.2	5.3	10.7	13.1	10.7	7.8	2.8	Elder
"	Saltgrass g/	.1	.6	2.8	3.5	4.2	3.4	1.2	"
Isleta	" i/	.6	4.8	5.5	6.1	5.6	3.8	.8	Blaney
"	Sedge j/	6.5	10.5	12.4	16.2	11.7	7.5	5.6	"
"	Willows k/	2.3	3.5	4.2	6.1	5.6	3.8	1.8	"
Mesilla	Saltgrass l/	2.0	2.1	3.8	9.2	7.9	6.1	4.1	"
Carlsbad	Saltgrass g/	3.2	4.7	7.2	11.8	9.2	7.6	4.3	"
"	Sacaton g/	4.5	6.4	5.8	8.1	7.1	6.1	3.5	"
"	Saltcedar g/	-	-	3.3	4.8	8.4	8.6	6.8	"
"	Saltcedar b/	-	-	1.9	4.3	8.2	6.1	6.1	"
"	Sacaton b/	3.1	2.7	6.6	6.7	7.8	5.7	3.8	"

a/ Water table 36 ins. b/ Water-table 48 ins. c/ Coastal area
d/ Mojave Desert e/ Water-table 12 ins. f/ Isolated tank
g/ Water-table 24 ins. h/ At Los Griego Station i/ Isleta Station
j/ Growing in water k/ Water-table 9 to 18 ins. l/ Water-table 14 ins.

Table 2—Examples of annual or seasonal consumptive use of ground water by phreatophytes and hydrophytes as measured by tanks or lysimeters in Western United States.

Locality	Type	Period	Depth to water table inches	Consumptive Use: Inches	Consumptive Use: Centimeters	Authority
ARIZONA						
Safford	Salt cedars*	Sept. 1943-Oct. 1944	--	86.4	219	(8)
Safford	Cottonwoods*	Sept. 1943-Oct. 1944	--	72.0	183	(8)
Safford	Baccharis*	Sept. 1943-Oct. 1944	--	56.4	143	(8)
Safford	Mesquites*	Sept. 1943-Oct. 1944	--	39.6	101	(8)
CALIFORNIA						
Santa Ana	Salt grass	May 1929-April 1932**	12	42.7	108	(1)
Santa Ana	Salt grass	May 1929-April 1932**	24	35.3	90	(1)
Santa Ana	Salt grass	May 1929-April 1932**	36	23.8	60	(1)
Santa Ana	Salt grass	May 1929-April 1932**	48	13.4	34	(1)
Santa Ana	Wire rush	Aug 1930-July 1931	24	78.9	200	(1)
Victorville	Tules	Jan 1931-Dec 1932	0	78.4	199	(1)
San Luis Rey	Tules	Jan 1940-Dec 1943	0	58.9	150	(10)
San Luis Rey	Cottonwoods*	April 1941-Mar 1943**	48	62.5	159	(10)
San Luis Rey	Cottonwoods*	April 1939-Mar 1941**	36	91.5	232	(10)
COLORADO						
San Luis Valley	Meadow grass	June-Nov 1936	0	36.3	92	(2)
San Luis Valley	Tules	June-Nov 1936	0	38.8	99	(2)
Ft. Collins	Sedge grass	May-Oct 1930	18	53.6	136	(15)
Ft. Collins	Rushes	July-Oct 1930	--	52.6	134	(15)
NEW MEXICO						
Los Griegos	Salt grass	Oct. 1927-Sept. 1928	26	22.7	58	(2)
Isleta	Sedge grass	June 1936-May 1937	3	76.9	195	(2)
State College	Cattails	July-Dec. 1936	30	44.2	112	(2)
State College	Salt grass	July-Dec. 1936	14		74	(2)
Carlsbad	Tamarisk	Jan.-Dec. 1940	36	57.3	146	(4)
Carlsbad	Sacaton	Jan.-Dec. 1940	24	48.1	122	(4)
Carlsbad	Sacaton	Jan.-Dec. 1940	48	41.4	105	(4)

*100 percent volume density. **Average yearly for period of record.

Relation of Consumptive Use to Evaporation

Meteorological conditions influencing evaporation from water surfaces likewise affect evaporation from soils and transpiration from vegetation. Both evaporation and transpiration freely respond to changes in termperature, wind movement and humidity so that evaporation from water may, under certain conditions, be used as an index of evaportranspiration losses for areas in which there is ample water to take care of evaporation and transpiration.

Studies which the author has made of water utilization in Rio Grande, Pecos River, and Colorado River basins, indicate that observed evaporation data from U. S. Weather Bureau pans may be used as a means of estimating evaportranspiration by water-loving vegetation when the relation of the two values is known for a particular area. This was accomplished in the Pecos River Joint Investigations (4) as illustrated in Table 3.

Table 3--Average computed rates of annual evapotranspiration by phreatophytes based on pan evaporation and climatic factors, Pecos River Basin, New Mexico and Texas

Location	Saltcedar along river	Computed evaportranspiration, inches		
		Saltcedar average	Brush areas away from river	Grass and weeds away from river
New Mexico				
Las Vegas	51.6	43.2	34.8	21.6
Fort Sumner	64.8	51.6	43.2	27.6
Roswell	67.4	56.4	45.6	28.8
Carlsbad	72.0	60.0	48.0	30.0
Texas				
Barstow	71.8	58.8	46.8	30.0
Balmorhea	72.0	60.0	48.0	30.0
Fort Stockton	72.0	60.0	48.0	30.0

The results of investigations in California, New Mexico and other areas indicate the observed evaporation data may be used as a means of estimating evapo-transpiration by phreatophytes and hydrophytes having access to an ample water supply when the relation of the two is known for a particular area (1, 2). As an example, for two locations in California, for tules growing in large tanks within the confines of a swamp area, the consumptive use, with reference to evaporation from a nearby exposed Weather Bureau pan, was 95 percent under desert and cold winter conditions at Victorville, and 94 percent under mild summer and winter climate near the Pacific coast at San Luis Rey (1, 2, 10). Some of the results of these investigations are shown in Table 4.

Table 4--Comparison of annual evapotranspiration by natural vegetation growing with water table at different depths to evaporation from a Weather Bureau pan, San Luis Rey Basin and Victorville, California.

Classification	San Luis Rey, Calif.			Victorville, Calif.		
	Depth of water table	Annual water consumption	Ratio water use to evaporation	Depth of water table	Annual water consumption	Ratio water use to evaporation
	Ft.	In.		Ft.	In.	
Pan evaporation	0.0	60.8	1.00	0.00	82.5	1.00
Tules	0.0	57.5	0.94	0.00	78.5	.95
Cottonwoods	3.0	92.7	1.52	--	--	--
Cottonwoods	4.0	62.3	1.02	--	--	--
Brush-grass	4.7	45.4	.75	--	--	--
Grass	12.0	14.0	.23	--	--	--

Determining Consumptive Use From Climatological Data

Actual measurements of consumptive use under each of the physical and climatical conditions of any large area are expensive and time consuming (3). Therefore, some rapid method of transferring the results of careful measurements, made in several areas, to other areas of similar conditions is needed.

From long-period records of evaporation, temperature and humidity in New Mexico and Texas, together with consumptive-use measurements at Carlsbad, New Mexico, empirical formulas were developed by Blaney and Morin for computing evaporation and consumptive use when temperature and humidity data are available (5). Consideration of these results and the factors involved is shown in the expression:

$$u = ktp\ (114-h) = kc = \text{monthly consumptive use}$$

in which "u" is the monthly consumptive (or evaporation) in feet; "k" is the monthly empirical coefficient; "t" is the mean monthly temperature, °F; "p" is the monthly percentage of daytime hours of the year; "h" is the average monthly humidity; and "c = tp (114 - h)" is the monthly use index (climatic factor). The formula for annual consumptive use is:

$$U = K_aC = k_wc_w + k_sc_s$$

in which "K_a" is the empirical coefficient for the entire year; "C" is the use index for the entire year; "k_w" is the empirical coefficient for winter period; "k_s" is the empirical coefficient for growing season or frost-free period; "c_w" is the use index for winter season; and "c_s" is the use index for growing season or frost-free period. The values of "k_w" and "k_s" were computed from observed values of evapotranspiration, temperature and humidity by the relation $k = u/c$.

Computed coefficients for winter and summer water consumption based on evapotranspiration, evaporation, temperature and humidity measurements in New Mexico are shown in Table 5.

Table 5--Coefficients for computing water consumption from climatological data.

Type of vegetation or land use	Depth of water table (feet)	Empirical coefficients k_w	k_s
Sacaton	4	0.0044	0.0139
Sacaton	2	0.0063	0.0154
Salt cedar (tamarisk)	2	0.0075	0.0216
Alfalfa	5	--	0.0174
Tules	0	--	0.0240
Evaporation, bare soil	2	0.0063	0.0083
Evaporation, water surface	0	--	0.0174

Table 6 illustrates computations of rates of use by phreatophytes along the Pecos River, New Mexico and Texas.

Table 6--Computed normal annual rates of consumptive use by groundwater vegetation grpwing along the Pecos River in New Mexico and Texas.

Station and frost-free period	Use index c_s	c_w	Annual consumptive use (U): Salt cedar (Tamarisk) Along river: Maximum 2/	Average 3/	Salt grass (Sacaton) Adjacent to river Moist areas 4/
NEW MEXICO			Feet	Feet	Feet
Las Vegas					
May 6-Oct 9	1911	1478	4.5	3.8	3.1
Ft.Sumner					
Apr 11-Oct 18	2434	1197	5.3	4.5	3.6
Roswell					
Apr 7-Oct 31	2641	1071	5.7	4.8	3.9
Carlsbad					
Mar 28-Nov 3	2795	1058	6.0	5.0	4.0

Table 6 Continued

Station and frost-free period	Use Index c_s	c_w	Annual consumptive use (U) Salt cedar (Tamarisk) Along river Maximum 2/	Average 3/	Salt grass (Sacaton) Adjacent to river Moist areas 4/
TEXAS			Feet	Feet	Feet
Grandfalls					
Mar 28 - Nov 1	3120	1195	6.5	5.6	4.5
Balmorhea					
Mar 29 - Nov 15	2765	936	5.8	4.9	4.0
Ft. Stockton					
Mar 31 - Nov 12	2836	1018	6.0	5.0	4.1

1/ Computed from formula $U = u_s + u_w - k_s c_s + k_w c_w$ = consumptive use in feet. Based measured data at Carlsbad, New Mexico.
2/ $k_s = 0.0019$ and $k_w = 0.0006$ Water table at 2 feet.
3/ $k_s = 0.0016$ and $k_w = 0.0005$ Average water-table
4/ $k_s = 0.0013$ and $k_w = 0.0004$ Water table at 4 feet.

Eradication and Control

The development of methods to eliminate and to control phreatophytic growth along stream channels, irrigation canals and in reservoirs to conserve water is one of the most perplexing problems to be solved in Western states. This is particularly true of salt cedar (Tamarisk). Large quantities of water are lost each year in river basins by use of water by these noxious plants such as salt cedar, cottonwood and willow. The rates of evaportranspiration by phreatophytes have been measured in some areas as indicated in Tables 1 and 2. In a few areas cottonwoods and willows have been eradicated by clearing the growth and by lowering the water table, and about 50 percent of the ground water has been salvaged for use of irrigated crops. However, effective eradication of salt cedar has not been very satisfactory, and more research is needed before this problem can be solved.

The growth of salt cedar in New Mexico for many years was confined largely to the lower valleys of the Pecos River and the Rio Grande, with heavy infestations in the delta areas of McMillan and Elephant Reservoirs. However, in recent years it has spread into the San Juan, Canadian and Gila River Basins. Also, salt cedar is spreading rapidly in the Upper Colorado River Basin. The State Engineer of New Mexico in cooperation with the U. S. Bureau of Reclamation has been studying this problem since 1947. A report (14) by Thompson in 1957 describes the occurrence and spread of phreatophytes over 440,000 acres in New Mexico.

After analyzing the available data in New Mexico and other states, Thompson came to the following conclusions:

"Evidence available at this time indicates that salt cedar is rapidly becoming the predominant nonbeneficial vegetation in the lower river valleys of the Southwest where high water table and climatic conditions are ideal for its growth. It is further evident that this plant is becoming established in the higher tributaries and is invading some of the stream systems of the Northwest. It is therefore believed that, due to its extremely high water consumption and the fact that it constitutes one of the major operation and maintenance problems on irrigation and flood control projects throughout the western states, Congressional legislation should be enacted and funds appropriated for a Federal program. It is further concluded that:

"1. At present channelization is the most effective means of salvaging water in the river channels and reservoir delta areas in the heavily silt-laden river basins of the West.

2. Significant amounts of water may be salvaged by the eradication of salt cedar and other phreatophytes.

3. A method of eradicating salt cedar must be found which is more effective and economical than those currently in use.

4. Finding a commercial use for salt cedar would afford a quick method of control.

5. Additional and more conclusive studies should be carried on to determine the consumptive use of phreatophytes.

6. The volume-density method of vegetative surveys should be adopted as a standard by all state and Federal agencies."

Many experiments on test plots have and are now being conducted in Arizona by Arle (11) of the Agricultural Research Service and Bowser of the U. S. Bureau of Reclamation. These studies have been made in the Gila River channel near Yma and in a tract in the Gila River flood plain southwest of Phoenix, Arizona.

After reviewing about 10 years work in Arizona and New Mexico, Arle reported (11) that:

"Although the considerable number of experiments and trials have not resulted in an entirely economical and practical method of killing saltcedar, valuable information on its control has been developed. This information may be summarized as follows:

"1. Saltcedar is more difficult to kill on flood plains than along irrigation channels and streams.

"2. Single spray operations have never given satisfactory total plant kill of adult saltcedar and only rarely have two repeated treatments eliminated 80 percent or more of the plants.

"3. Periodic spraying of infested areas with 2, 4-D and 2, 4, 5-T will defoliate saltcedar and in this manner reduce transpiration losses.

"4. Applications of 2, 4-D and related materials appear more effective on young regrowth following mechanical destruction than on adult saltcedars.

"5. Application rates of less than 2 pounds per acre have generally given poor results.

"6. Low-volatile esters of 2, 4-D or combinations of 2, 4-D and 2, 4, 5-T have been consistently more effective than amine or sodium salts of 2, 4-D.

"7. Dormant applications of 2, 4-D and 2, 4, 5-T esters have shown promise in the control of saltcedar.

"8. Mechanical means, although expensive, are useful in the eradication of saltcedar, especially in areas near cotton or other crops susceptible to 2, 4-D.

"9. Mechanical control must be exercised at least yearly to eliminate regrowth from root sprouts and seedlings.

"10. Saltcedar is more difficult to kill with 2, 4-D and related materials than most willows, cottonwood, and other woody phreatophytes.

"11. Mechanical clearing followed by spraying of young regrowth with 2, 4-D or a mixture of 2, 4-D and 2, 4, 5-T at 2.5 pounds or more per acre repeated as necessary once or twice a year appears to be the most effective and practical method now known for controlling saltcedar."

The Corps of Engineers, U. S. A., reported (11):

"Estimates of phreatophyte infestation and water consumption in New Mexico showed that 441,000 acres occupied by phreatophytes wasted nearly 900,000 acre-feet of water a year. Nevada's phreatophyte infestation is placed at 2,801,000 acres, and the annual water loss at 1,500,000 acre-feet."

A recent report by the Bureau of Reclamation to the U. S. Army, Corps of Engineers, on the proposed clearing of 13,840 acres of predominantly saltcedar growth in the Safford Valley of the Gila River estimates the consumptive use is 47,840 acre-feet before clearing and 13,840 acre-feet after clearing. The salvage would be 34,000 acre-feet of which 19,800 acre-feet could be diverted to irrigate farms and put to beneficial use.

In 1943, Blaney estimated that if 5,000 acres of Gila River bottom land above San Carlos Reservoir in Arizona were cleared of saltcedar, cottonwoods and other phreatophytes, about 50 percent of the water used by this vegetation, amounting to 15,000 acre-feet per year, could be salvaged for use in producing copper during World War II.

A five-year study by Muckel and Blaney (10) in the San Luis Rey Basin in San Diego county, California, indicated that 52 percent or 9,280 acre feet could be salvaged from 6,390 acres of cottonwoods, willows and brush if the land was cleared and the water-table was lowered rapidly below the root zone. This was eventually done and the river bottom planted to alfalfa and vegetables.

A two year (1945-46) study by Muckel and Blaney of water losses in the Santa Ana River Canyon, California, for five miles below Prado Dam, indicated that 1,407 acre-feet of water could be salvaged (47 percent) if the 1,071 acres of cottonwood and willow were converted to sparse growths, by piping the water from the dam to intakes of two mutual water companies. These companies supply water for irrigation of orange trees.

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