Water Resource Conservation by Reducing Phreatophyte Transpiration

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Through managing the magnitude of depth to the water table below floodplains supporting phreatophytes, water conservation may be effected due to resulting reductions in evapotranspiration, while the integrity of the riparian ecosystem is maintained. A model of the phreatophyte-floodplain system has been developed for analyzing the method's economic feasibility.

INTRODUCTION AND SCOPE

In the past, water conservation by reducing phreatophyte transpiration has most often involved eradication methods, which have presented a conflict between the interest in saving the large amount of water the plants use, and the interest in the values that come with preserving a natural riparian ecosystem. An alternative conservation method to eradication is presented here, which can maintain the riparian stand and thus reconcile the conflict, if the method proves feasible.

Evidence exists to support a relationship between depth to the water table below phreatophyte-floodplain systems, and the evapotranspiration ($E_t$) rate from them. By managing the position of the water table at increased depths, yet within the range of phreatophyte root extension (salt-cedar roots have been excavated to depths of 30 meters), the $E_t$ rate can be reduced while maintaining environmental integrity. Thus, hypothetically, pumps or drains would be installed in floodplain alluvium supporting phreatophytes. The water table would be lowered to a deeper position, resulting in a reduction in $E_t$ after the phreatophyte root termini have deepened to the new position of the capillary fringe. If the pumped water can be substituted into regional demand, then the reduction in $E_t$ rate represents salvaged water.

The scope of the analysis of this conservation strategy here includes the magnitude of possible $E_t$ reductions and the cost feasibility. A modeling methodology is used. Certainly, the feasibility of this conservation method will also be constrained by the political and legal implications of affecting a stream-aquifer system including the possibility of prior appropriations and of instream requirements.

A HISTORY OF WATER CONSERVATION BY REDUCING PHREATOPHYTE $E_t$

After recognizing the relation between certain species of desert plants and the water table, O. E. Meinzer (1923, 1927) introduced the term phreatophyte (the Greek roots phreatos = well, phuton = plant) which he defined as "a plant that habitually obtains its water supply from the zone of saturation, either directly or through the capillary fringe." Early studies demonstrated this relationship by locating observation wells in phreatophyte areas and observing their influence on the water table.

Later, toward the middle of this century, the study of phreatophytes in arid areas of the western United States began to proliferate, no longer because of their usefulness, but because of their water use. Robinson (1958) attributes concern over water supply problems at this time to a prolonged drought contemporaneous to a post World War II increase in water demand, and to the spread of one non-native species, Tamarix chinenses Lour., through the stream valleys of the Southwest. Also, shortly before this time Gatewood et al. (1950), in studying the Safford Valley, Arizona to determine possible water salvage for the war industry in 1943-44, used water balance methods to measure evapotranspiration. They were perhaps the first to draw attention to the potentially large amounts of water transpired by Tamarix sp.

In 1952, Robinson estimated that phreatophytes covered 16 million acres in the western states and consumed 25 million acre-feet of water per year. While noting that these numbers may be "greatly exaggerated", Van Hylckama (1982) points out:
Robinson's data served to create active, even alarmist interest in the phreatophyte problem... In the literature, salt cedars have been described as "waterhogs" (Douglass, 1954), "aggressive" (Robinson, 1965), "greedy" (Douglass, 1965), "insidious" (Sebenik and Thames, 1968), "thieves" (Robinson, 1952) and "water stealing culprits" (U.S. Information Service, 1965). These expressions indicate the emotional and propagandistic attitude that is sometimes taken towards the phreatophyte problem.

In light of his estimates, Robinson proposed the study of water salvage by either 1) replacing the plants with more beneficial ones, 2) intercepting water upstream of the plants, 3) directly destroying the phreatophytes, or 4) lowering the water table out of their reach and thus killing them. Thus began the proliferation of research into water salvage and also into measuring $E_t$ to justify water conservation projects. By 1964, Robinson had published a report of 48 projects relating to the phreatophyte problem. Bibliographies containing together over 2,000 titles related to $E_t$ and phreatophytes have been compiled by Robinson and Johnson (1961), Humphreys (1962), and Horton (1973).

Eradication projects to destroy and replace phreatophytes include those such as Bowser (1952), Koogler (1952), and Cramer (1952). Fox (1977) points out that the Los Angeles report of the Phreatophyte Subcommittee of the Pacific Southwest Inter-Agency Committee in 1969 lists nearly two dozen major clearing projects in Arizona. The best documented and most recent of these (Culler et al., 1982) is the eradication of some 5,000 acres on the Gila River floodplain, producing a measured reduction of 480 mm in yearly $E_t$.

No evidence in the literature has been found of further attempts to eradicate phreatophytes for water salvage, probably due to factors including the rapid regenerative properties of Tamarix sp., and the objectionable environmental consequences including loss of wildlife habitat and bee pasture, the lowered aesthetic quality, and the increase caused in erosion. Out of concern for the riparian habitat, a conference was held in 1977, titled Symposium on Importance, Preservation and Management of the Riparian Habitat, dedicated to Douglas C. Harrison whose research quantified the effects of phreatophyte control on the breeding of birds in the native riparian woodland of the Verde River.

As an alternative to eradication, substances have been applied to phreatophytes to reduce transpiration, as proposed by Horton (1976), Ffolliott and Thorud (1975), and Affleck (1975). Davenport et al. (1978) measured the $E_t$ reduction and environmental effects due to various antitranspirants (AT). They concluded that ATs safely and significantly reduce $E_t$ but were uneconomical to apply. At their estimated application rate of $135$/acre/month to produce a 25% $E_t$ savings (.007 ft/day) on Tamarix sp., the cost is about $634$/ac-ft of water saved/year.

Lowering the water table below floodplains has been previously investigated. Early analyses were done in 1956 by the Bureau of Reclamation (reported by Affleck, 1975), in which a multiple regression equation using air temperature, precipitation, and depth to ground water was used to predict that a five-foot lowering of the water table below the Gila River from Thatcher to Glenbar, Arizona, would effect water savings of about 7,000 ac-ft annually. Bouwer (1975) presented iterative and analytical procedures for computing seepage from streams which incorporated $E_t$/water-depth relations for application to the phreatophyte problem.

RELATIONSHIP BETWEEN $E_t$ AND DEPTH TO WATER

A phreatophyte-floodplain system is here defined as the relationship between an unconfined, alluvial aquifer, a perennial stream, and phreatophytes with root termini in the capillary fringe (Figure 1). $E_t$ from this system can be thought of as a function of three interdependent influences including 1) the availability of energy at the evaporating surface to supply latent heat demand, 2) the vapour pressure gradient between the water at the evaporating surface and the bulk air, and 3) the resistances in the water flow pathways (Hillel, 1982; Slayter, 1967). Thus, in the phreatophyte-floodplain system, in addition to factors at the surface of or external to the evaporating bodies (atmospheric evaporativity), $E_t$ will be a function of water pathway characteristics in the soil as well as resistance to water movement within the vegetation.

It is the increase in pathway resistance in relation to depth of the water table beneath the floodplain system ($D$) that is of interest. In studying evaporation from bare soils, Gardner
From these, some cross sectional data are plotted. Bouwer (1975) has suggested a sigmoidal model.

Figure 2.--Et/D data.

In addition to reduced soil evaporation, the literature suggests although the data are limited, that with other factors remaining constant, phreatophytes will transpire less water with increasing D. Excavation studies have shown that phreatophytes concentrate root termini in the capillary fringe (Tomanek and Ziegler, 1963; Gary, 1965). Thus, with an unrestricted water supply, the plants can be thought of as always transpiring at the potential rate, which will lessen with increased root depth. A rigorous explanation for the relation of this phenomenon to resistances in plant pathways for water transport is not yet known. It should be noted that certain phreatophytes may exist in the absence of a water table. Turner (1974) made a distinction between facultative phreatophytes and obligate phreatophytes. The latter need uninterrupted access to the water table, while the former including Prosopis sp. and Tamarix sp., may survive indefinitely in the absence of saturated soil as xerophytes. However, this analysis will be concerned only with systems having a capillary fringe within rooting range.

In a survey of field studies measuring the water consumption of riparian vegetation, ten were found having Et/D data. The majority involve applying water balance methods to evaporotranspiration meters where D is varied between 1 and 3 meters. From these, some cross sectional data are plotted in Figure 2. The data from Van Hylckama (1974) suggest a linear Et/D relationship, having a correlation coefficient above 0.95; however, extrapolating to the abscissa gives the absurdity of zero Et for Tamarisk with D greater than 4 meters. Thus Bouwer (1975) has suggested a sigmoidal model. Unfortunately more data outside of the D range of 1 to 3 meters such as that shown from Harr and Price (1972) do not exist. The data from Gatewood et. al (1958) show a relationship; however, their volume-density correction has been questioned (Van Hylckama, 1974).

**METHODOLOGY**

For an analysis of the system, constant evaporativity is assumed, and thus annual Et volume for a given community is only a function of D:

$$E_t \text{ Annual Volume} = \int E_t(D) \, dD \, dA$$

where: $A = \text{surface area of the floodplain} \quad (L^2)$

In the absence of well defined Et/D relationships, we can assume them and examine their sensitivity. An empirically based equation giving a sigmoidal curve is used to model the Et/D relationship:

$$E_t = \frac{E_{t,\text{MAX}}}{1 + (D/C)^\alpha}$$

where: $E_{t,\text{MAX}} = E_t(0) \quad (L/T)$

$\alpha, C = \text{empirical constants} \quad (\text{dimensionless}, L)$

Curves for various $\alpha, C$ (C in meters) are plotted in Figure 3. It is assumed that root adjustment is instantaneous with D. In addition, it is assumed that the evaporation rate from the water surface of the river occurs at rate equal to $E_{t,\text{MAX}}$. The latter assumption will tend to over-estimate $E_t$, because the evaporating surface of plants may greatly exceed the land area beneath their canopy, and this greater surface area more than compensates for the additional resistance in the water vapor pathway (Slayter, 1967). Examination of Figure 3 shows that because the $E_t/D$ relationship is nonlinear, lowering the water table from 5 feet below ground surface to 6 feet below will cause greater reductions in $E_t$ than lowering it an equal amount but from 25 feet below to 26 feet below. Thus, certain segments of the $E_t/D$ curve can be thought of as being more effective in terms of the reduction in $E_t$ effected by a unit change in D.

**Figure 2.--Et/D data.**

**Figure 3.--Et/D Models.**
If Dupuit assumptions are made with respect to ground water flow, a two dimensional finite difference model for aquifer simulation (Trescott et al., 1976) can be used, and equation 2 included as a source term to evaluate various dewatering scenarios. $E_t$ was made a function of average $D$ at the 2 previous iterations to assure stability of the finite difference scheme.

In defining parameters and boundary conditions for the model, it is assumed that the floodplain aquifer can be represented by a prism of homogeneous and isotropic material symmetric in shape to the river. Average dimensions are based on the Gila River, Arizona (Culler et al., 1982) including width, thickness, topography and channel dimensions. Yearly averages for streamflows, recharge and underflow are used, thus ignoring the seasonality of these components. Dirichlet boundary conditions are used at all aquifer boundaries, and a head dependent source term is used at the river. Recharge and discharge wells normal to the river at its ends, are used to simulate underflow.

**RESULTS**

The prepumping, steady state water balances resulting from using $E_t/D$ models with $a,C$ of 4, 2.5 and 1.5, 3.5 are compared to estimates for the Gila River in Table 1. Both, while representing different systems, fall within the range of estimates made for the Gila.

With pumping wells arbitrarily spaced 4,000 feet apart and 1,300 feet from the river on either side, it was possible to pump each well at a maximum of 2.2 ft$^3$/s without the wells going dry when drawdown was calculated in a 1-foot well radius. The effects of this pumping scenario on the water table were observed after one year and again after steady-state conditions had been reached. Table 2 summarizes the computed $E_t$ savings with the varied pumping rates, duration, and values of $a,C$.

Costs of water saved by lowering the water table include well field installation, operation, and maintenance costs. However, when both fixed and maintenance costs are amortized over the life of the pumping system, they become negligible to energy costs. In light of this and the fact that fixed cost estimates are subject to large variation, only energy requirements will be analyzed.

Power plant and pump efficiency were assumed to be 50%. Electric pumping plants were assumed along with an energy cost of $0.08/kw-hr. Based results by Campbell & Lehr (1973), at 50% efficiency pump power consumption is 1.5 kw/HP. Results are compared in Table 3.

**DISCUSSION**

For the $E_t/D$ models and pumping scenario used, the steady-state results of $E_t$ reduction range from 20 to 45%. For perspective, if Robinson's 1952 estimate of 25 million ac-ft/yr for phreatophyte consumption were reduced by 20%, the resulting saving would amount to over three times the annual amount of water to be provided by the Central Arizona Project (assuming annual deliveries of 1.5 million ac-ft, Arizona Department of Water Resources, 1980).

The results show that a maximum reduction in $E_t$ for this scenario occurs with the model having $a,C$ values of 2.5, 4 m with a pumping rate of 2.2 ft$^3$/s. Increasing the pumping rate by 22% from 1.8 to 2.2 ft$^3$/s causes a 4 to 7% increase in $E_t$ savings, and yet the energy costs for any rate are under $50/ac-ft of water saved. The volume of water produced by pumping is 4 to 6 times the volume of water saved by reducing $E_t$. A continual pumping rate of 2.2 ft$^3$/s represents roughly a 3,000 ac-ft/yr per 4,000 ft of river water supply at a cost below $10/ac-ft. Clearly these costs are low when compared to other large southwestern water projects such as the Central Arizona Project, for which estimates of actual water costs have been as high as $300/ac-ft.

The cross sections of the floodplain in Figure 4 show that river flow is slightly maintained for $a,C$ of 2.5, 4 at maximum $D$, but is not for the other system. These results are important from an environmental standpoint. Clearly, the phreatophyte system is maintained in either case; however, the non-phreatophyte component of the riparian ecosystem would be altered. Thus, pumping rate must be constrained by instream water requirements to maintain environmental integrity.

It is interesting to note that the maximum reduction in the $E_t$ rate for a given set of conditions is approached or reached by the end of the
Table 2.--Computed \( E_t \) savings with aquifer dewatering using the eight-well scenario

<table>
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<th>( \alpha_C )</th>
<th>1.5,3.5</th>
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<tr>
<td>Pump rate (ft³/s)</td>
<td>1.8</td>
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<td>Duration</td>
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<td>9.13 yrs</td>
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<td>Energy requirement (kw-hr/yr-pump)</td>
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<td>93051</td>
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<tr>
<td>Cost/yr-pump ($)</td>
<td>7390</td>
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<td>Cost/af ($)</td>
<td>35.89</td>
<td>35.42</td>
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First year. This results from the assumption of an instantaneous root adjustment by the plants. How root systems of phreatophytes will respond to dewatering is not well known. Tamarisk roots have been measured to grow 30 inches in the first year to the bottom of phytometers by Merkel and Hopkins (1957) and Tomanek and Ziegler (1963). The latter authors have suggested that maximum root depth may be determined by the position of the water table at a critical time in the life of the plant. Unfortunately, time series data for root extension do not exist. If the roots of one generation of plants are in fact not capable of recovering to a new position, it may take generations of plants with increasing root depth before steady state is reached.

The achieved 45% reduction in \( E_t \) is not the maximum possible for the systems evaluated. To compute a maximum, future hydraulic modeling efforts can be linked to management models to optimize pumping scenarios (see for example Maddock, 1973 and Aguado and Remson, 1980).

CONCLUSIONS

The positive results of this analysis will hopefully encourage continued research into managing water table positions in phreatophyte floodplain systems as a feasible method of water resource conservation.

Clearly the nature of the \( E_t/D \) relationship needs to be better defined. In situ measurements of phreatophyte response to altered water table positions including \( E_t \) rate, canopy response, and root depth changes are crucial to understanding the feasibility of this approach. Unfortunately, despite the tremendous effort in past phreatophyte research, this still remains a complex and expensive proposition. New advances in remote sensing of \( E_t \) (Reginato et al., 1985) and in psychrometric methods (Gey, 1979) might prove useful for \( E_t \) measurements.

A survey of classifications of riparian-phreatophyte communities has shown that the variation in them in the Southwest is relatively small (see for example Campbell, 1970; Marks, 1950; or Haase, 1972). Ideally, a distinct \( E_t/D \) relationship could be defined for each community, or perhaps a small number of curves for each as they vary with climate or elevation.

LITERATURE CITED


Arizona Department of Water Resources. 1980. (Oct.) Colorado River operation and supply studies. [unpublished report]


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