Predicting Reduction in Water Losses From Open Channels by Phreatophyte Control

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A procedure is presented for calculating seepage from a stream due to uptake of groundwater by vegetation or evaporation from soil in the floodplain. The calculation requires that the relation between evapotranspiration rate and water table depth be known. If these relations are available for a given floodplain before and after removal of phreatophytes, the reduction in seepage losses from the stream due to phreatophyte removal can be computed. To simplify the calculation process, the curves relating evapotranspiration rate and water table depth, which are generally sigmoid, can be approximated by step functions of the same area. Potential water savings by phreatophyte control are calculated for step functions that are representative of deep-rooted vegetation, shallow-rooted vegetation, and bare soil. In addition to the depth from which groundwater can be evaporated before and after phreatophyte removal the water savings are affected by the vertical distance between the water level in the stream and the floodplain.

Phreatophytes have been estimated to cover 6.4 million ha in the western United States and to consume about 30,000 million m³ of water per year [Robinson, 1958]. At 100% cover, salt cedar used 2.2, cottonwood 1.8, baccharis 1.4, and mesquite 1.0 m of water per year in the lower Safford Valley of Arizona [Gatewood et al., 1950]. An extensive bibliography on phreatophytes has been prepared by Horton [1973]. Phreatophytes generally grow in floodplains, and they derive a significant part of their water needs from the groundwater. Where this groundwater is supplied by seepage from streams or canals in the floodplain, the water loss from these channels can be reduced by removing deep-rooted phreatophytes and replacing them with shallow-rooted vegetation or bare soil.

Two basic approaches have been used to estimate the reduction in water losses that can be obtained by phreatophyte control. One has been to grow phreatophytes in large containers (evapotranspirimeters) and to determine their water use as the amount of water that needs to be added to maintain the water table at a constant depth [Turner and Halpenny, 1941; Blaney et al., 1942; Gatewood et al., 1950]. Various containers with different water table depths have sometimes been used [van Hylckama, 1970, 1974]. The other approach is to measure the components of the water balance for a certain reach of a floodplain. The water used by the vegetation in the floodplain is then evaluated as the difference between the sum of all inflow components and the sum of all outflow components for the reach. If this is done before and after phreatophytes are removed, the reduction in water losses from the stream can be determined [Hanson et al., 1972]. Other techniques, such as evaluating the water use from groundwater levels or gradients, seepage measurements, or changes in the salt concentration of the groundwater have also been used [Gatewood et al., 1950].

The evapotranspirimeter approach is limited because of the difficulty in transferring the data to an entire floodplain with mixed densities, ages, and species of plants [van Hylckama, 1970], particularly if the container is relatively small and has only one plant. Also it cannot be assumed that the amount of water used by phreatophytes in tanks will be the amount of water saved when the phreatophytes are removed from the floodplain because after removal the water table may rise closer to the surface where it could be within reach of shallow-rooted 'replacement' vegetation. The water table may even rise high enough for evaporation from bare soil to become significant. Thus groundwater levels after removal of the phreatophytes must be predicted before the water saving can be estimated.

A disadvantage of the water balance approach is that considerable time and effort are needed to measure or estimate the components of the water balance for a certain stream reach. Also the error in the evapotranspiration rate computed by the water balance method may be quite large because this error represents an accumulation of the errors in each component. It may be necessary to remove phreatophytes from a considerable area to affect the water balance measurably. Thus a rather involved phreatophyte control project may be required to determine how much water can be saved.

Often it is desirable to estimate the water saving by phreatophyte control without large investigations or test projects. Such estimates can be obtained if the relationships between evapotranspiration rate fₑ and depth of the water table h are known for the floodplain before and after removal of the phreatophytes. Essentially horizontal and stable water tables unaffected by the particular fₑ-h relation in the floodplain can be expected for confined, relatively narrow valleys underlain by very permeable aquifers at small depth. The reduction in seepage losses from the stream can then be evaluated directly from the fₑ-h relations before and after removal of the phreatophytes. Where these conditions do not occur, however, the water table slopes away from the stream channel, and the depth of the water table at any point depends on the particular fₑ-h relation. In that case, the water table after removal of phreatophytes will be higher than it was before, and fₑ-h relations alone cannot give reliable estimates of water savings in the stream. However, if seepage losses from a stream could be calculated for a given fₑ-h relation, the water saving could be evaluated as the difference between the calculated seepage rates for the fₑ-h relations before and after removal of the phreatophytes.

A procedure for calculating stream seepage for a given relation between fₑ and h in the floodplain is presented in this paper. Although realistic data on relations between fₑ and h are scarce and certainly not yet available for a wide spectrum of vegetation, soils, and climate [Rantz, 1968], it is hoped that...
the usefulness of such relations in calculating water losses from streams and potential water savings by phreatophyte control will stimulate additional research and the development of meaningful relations between evapotranspiration rate and water table depth. Inasmuch as \( f_e \) in this paper will be used to calculate water uptake by plants from groundwater, the portion of the total evapotranspiration that is extracted from the groundwater should be considered only when one develops \( f_e-h \) relations for seepage calculation.

**Calculating Water Losses Due to Evapotranspiration in the Floodplain**

Uptake of groundwater by plant roots varies diurnally and seasonally. The uptake is also affected by rainfall and other weather conditions, by periods of plant dormancy, and by the salinity of the groundwater [van Hylckama, 1970, 1975]. The flow and water levels in the stream are subject to variation, as are the bottom conditions in the channel because of changing scour and fill patterns. Water tables in the floodplain may be affected by sources and sinks other than seepage from the stream and evapotranspiration, respectively. Examples of potential sources are deep percolation from irrigation, upward flow from deeper artesian aquifers, and recharge along the sides of the floodplain. An example of a sink would be leakage into a lower aquifer. Soil and hydrogeological conditions are never uniform. Thus the flow system is very complex and must be simplified before it is amenable to theoretical analysis.

In this paper, stream seepage will be considered the only source, evapotranspiration the only sink, and the soil will be considered uniform with an impermeable layer as the lower boundary. The system will also be considered to be at steady state. The period for which a steady state can be assumed may range from a day to a year, depending on how conditions vary with time, on the accuracy desired, and on the available data. Although this paper only deals with one steady state condition to demonstrate the principles, in practice, several \( f_e-h \) relations and channel conditions may be included to allow for seasonal or other variations.

**Relation between evapotranspiration rate and water table depth.** Figure 1 shows the general nature of \( f_e-h \) relations. The deeper the roots, the greater the depth of the water table at which the vegetation can maintain essentially potential evapotranspiration rates. When the water table drops below the zone where most of the roots occur, the evapotranspiration rate is reduced until eventually the roots can no longer absorb groundwater. This is indicated when \( f_e \) becomes essentially zero at a certain value of \( h \). However, this does not mean that the evapotranspiration rate of the plants as a whole will be zero at that point, because roots may take up water from rain or water stored in the soil above the water table. For bare soil, evaporation also does not become zero when the water table drops to relatively large depth. Even then, water will continue to move upward in the soil, but part of the transport will be in the vapor phase [Jackson et al., 1973; Ripple et al., 1972]. When vapor transport occurs, the evaporation rates are quite small and can be taken as essentially zero.

Because roughness and total leaf area tend to increase with increasing plant height, and trees and shrubs generally have deeper roots than grasses and other low-growing plants, the potential evapotranspiration rate for deep-rooted vegetation is shown somewhat higher than that for shallow-rooted vegetation, which in turn is taken higher than that for bare soil. The \( f_e-h \) relation can be expressed on a daily, weekly, monthly, seasonal, or annual basis, depending on the available data and on the refinement desired in the calculation of water losses from the channel.

In developing \( f_e-h \) relations for a specific case, results from evapotranspiration studies, measurements of depth and distribution of root systems, estimates of potential evapotranspiration rates, and similar data may be used [Rantz, 1968]. New developments in computer modeling of water uptake by root systems [Whisler et al., 1968] may also prove useful in deriving \( f_e-h \) relations. For bare soils, \( f_e-h \) relations may be estimated from vertical unsaturated flow [Ripple et al., 1972], although evaporation from bare soil is by no means a simple process [Jackson et al., 1973]. Field studies of evaporation from sand in relation to water table depths were reported by Hellwig [1973] for the Swakop River in southwest Africa. Once the \( f_e-h \) relation is known, seepage losses from a stream due to evapotranspiration in the floodplain can be computed, as shown in the next sections.

**Calculation of channel seepage.** The floodplain is assumed to be underlain by an impermeable layer so that the seepage flow system below the water table can be analyzed on the basis of horizontal flow. This analysis is sufficiently accurate if the vertical distance of the impermeable boundary below the channel bottom does not exceed 3 times the width of the channel [Bouwer, 1969], or \( D_t < 3 W_t \) (Figure 2). If the impermeable layer is at a greater depth, an effective depth of this layer can be used to estimate accurately the seepage with the horizontal flow assumption. This effective depth, which is less than the actual depth of the impermeable layer, can be evaluated from seepage solutions obtained by other means for systems with deeper impermeable layers [Bouwer, 1969]. If the channel is in layered soil, the effective depth of the impermeable layer can be evaluated similarly. The hydraulic conductivity of the soil materials can be measured with techniques described by Bouwer and Jackson [1974]. The flow is also assumed to be two dimensional (normal to the stream only).

The steady state seepage from a stream or channel due to uptake of groundwater by floodplain vegetation, in accordance with certain \( f_e-h \) relations, will be calculated with a numerical procedure. The horizontal flow away from the channel will be considered for a certain increment \( i \) at some distance from the channel. The length of this increment is \( \Delta L_t \), and the increment is bound by water table depths \( h_{i-1} \) and \( h_i \) (Figure 2). Values of \( h_{i-1} \) and \( h_i \) must be selected so that the corresponding \( f_e \) rate within the increment is relatively uniform. The evapotranspiration within the increment \( \Delta L_t \) can then be taken as the average of \( f_e \) at \( h_{i-1} \) and \( f_e \) at \( h_i \). If this
average evapotranspiration rate is represented by \( \dot{f}_e \), the flow at a distance \( x \) from the inflow side of the increment \( \Delta L_i \) can be described as

\[
Q_{i,x} = Q_{i,1} - \dot{f}_e x
\]

where \( Q_{i,1} \) is the flow per unit length of channel at distance \( x \) from the inflow side of increment \( i \), and \( Q_{i,x} \) is the flow per unit length of channel entering increment \( i \). Since

\[
Q_{i,1} = Q_{i,2} + \dot{f}_e \Delta L_i
\]

where \( Q_{i,2} \) is the flow leaving increment \( i \), (1) can be written as

\[
Q_{i,x} = Q_{i,1} + \dot{f}_e x - \dot{f}_e x
\]

According to horizontal flow theory, \( Q_{i,x} \) can also be written as

\[
Q_{i,x} = -KH_{i,x} \frac{dH}{dx}
\]

where \( K \) is the hydraulic conductivity (length/time), and \( H_{i,x} \) is the vertical distance between the water table and the impermeable layer at distance \( x \) from the inflow side of increment \( i \) (Figure 2). If the height of the capillary fringe is not negligibly small in comparison with \( H \), the value of \( H \) should be taken as the vertical distance between the top of the capillary fringe and the impermeable layer. [Bouwer, 1964].

Equating (3) and (4) yields

\[
-KH_{i,x} \frac{dH}{dx} = Q_{i,2} + \dot{f}_e \Delta L_i - \dot{f}_e x
\]

which after integration between \( x = 0 \), \( H_i = H_{i,1} \), and \( x = \Delta L_i \), \( H_i = H_{i,1} \), and rearrangement of terms yields

\[
\dot{f}_e (\Delta L_i)^2 + 2Q_{i,2} \Delta L_i - K(H_{i,1}^2 - H_{i,2}^2) = 0
\]

To calculate the seepage from the channel, the first increment \( \Delta L_i \) is taken from the point where the water table has reached the depth \( h_a \) where \( \dot{f}_e = 0 \). At this point, the water table has theoretically become horizontal. Thus \( h_a, \Delta L_i \), will be equal to \( h_a \), and \( Q_{i,1} \) will be equal to zero (Figure 2). A value of \( h_{i,1} \), slightly less than \( h_a \), is now selected, and \( \dot{f}_e \), is determined from the graph of \( \dot{f}_e \) versus \( h_i \). Since \( Q_{i,2} = 0 \), (6) for \( \Delta L_i \) reduces to

\[
\dot{f}_e (\Delta L_i)^2 = K(H_{i,1}^2 - h_a^2)
\]

or

\[
(\Delta L_i)^2 = \frac{K}{\dot{f}_e} (H_{i,1}^2 - h_a^2)
\]

where \( H_d \) is the vertical distance between the water table and the impermeable layer where \( h \) has reached \( h_a \) (Figure 2). After \( \Delta L_i \) is calculated with (8), \( Q_{i,1} \), for \( \Delta L_i \) is computed as \( \dot{f}_e, \times \Delta L_i \). This then becomes \( Q_{i,2} \), for the second increment \( \Delta L_i \) to the left of \( \Delta L_i \). Then \( H_{i,3} \), for \( \Delta L_i \), becomes \( H_{i,2} \) for \( \Delta L_i \). A value is selected for \( h_{i,3} \), after which \( \dot{f}_e \), is determined from the graph of \( \dot{f}_e \) versus \( h_i \). These values are substituted into (6) to calculate \( \Delta L_i \). The value of \( H_{i,1} \), is calculated as the depth of the impermeable layer minus \( h_{i,3} \) (Figure 2). The inflow \( Q_{i,3} \), for \( L_{i,2} \) is calculated as \( Q_{i,2} + \dot{f}_e, \times \Delta L_i \), which is the outflow \( Q_{i,2} \), for the third increment \( \Delta L_i \) to the left of \( \Delta L_i \). This procedure is repeated until \( H_{i,1} \), has become \( H_{w} \), at which time the edge of the channel is reached, and \( Q_{i,4} \), for the increment \( \Delta L_i \) at the channel edge is the seepage from one side of the channel. If the flow system is symmetrical, the total seepage per unit length of channel is \( 2Q_{i,1} \). An example of this procedure is presented in the following section, after which it will be shown how the incremental procedure can be reduced to a simple equation for direct calculation of the seepage.

**Example.** To illustrate the procedure, seepage will be calculated for the channel in Figure 2, taking \( h + H = 10 \text{ m} \), \( h_a = 0.5 \text{ m} \), and \( K = 900 \text{ m/yr} \). The floodplain is assumed to be covered with salt cedar, for which the relation between \( h \) and \( H \) is shown in Figure 3. The circled dots in this graph were
TABLE 1. Calculation of Seepage With Incremental Procedure for System Described in Figures 2 and 3

<table>
<thead>
<tr>
<th>Increment of $L$, m</th>
<th>$h_2$, m</th>
<th>$h_1$, m</th>
<th>$\frac{\Delta e}{\Delta L}$, m</th>
<th>$Q_2$, m³/yr/m</th>
<th>$Q_{\Delta e}$, m³/yr/m</th>
<th>$Q_1$, m³/yr/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.5</td>
<td>5.0</td>
<td>0.04</td>
<td>4.5</td>
<td>5.0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>5.0</td>
<td>4.5</td>
<td>0.10</td>
<td>5.0</td>
<td>5.5</td>
<td>13.08</td>
</tr>
<tr>
<td>3</td>
<td>4.5</td>
<td>4.0</td>
<td>0.21</td>
<td>5.5</td>
<td>6.0</td>
<td>25.37</td>
</tr>
<tr>
<td>4</td>
<td>4.0</td>
<td>3.5</td>
<td>0.40</td>
<td>6.0</td>
<td>6.5</td>
<td>41.60</td>
</tr>
<tr>
<td>5</td>
<td>3.5</td>
<td>3.0</td>
<td>0.65</td>
<td>6.5</td>
<td>7.0</td>
<td>63.09</td>
</tr>
<tr>
<td>6</td>
<td>3.0</td>
<td>2.5</td>
<td>1.00</td>
<td>7.0</td>
<td>7.5</td>
<td>89.04</td>
</tr>
<tr>
<td>7</td>
<td>2.5</td>
<td>2.0</td>
<td>1.40</td>
<td>7.5</td>
<td>8.0</td>
<td>120.22</td>
</tr>
<tr>
<td>8</td>
<td>2.0</td>
<td>1.5</td>
<td>1.90</td>
<td>8.0</td>
<td>8.5</td>
<td>155.63</td>
</tr>
<tr>
<td>9</td>
<td>1.5</td>
<td>1.0</td>
<td>2.27</td>
<td>8.5</td>
<td>9.0</td>
<td>195.78</td>
</tr>
<tr>
<td>10</td>
<td>1.0</td>
<td>0.5</td>
<td>2.45</td>
<td>9.0</td>
<td>9.5</td>
<td>237.09</td>
</tr>
</tbody>
</table>

Increment of $L$, $h_2$, $h_1$, $\frac{\Delta e}{\Delta L}$, $Q_2$, $Q_{\Delta e}$, and $Q_1$ calculated with the incremental procedure.

The values of $h$ are selected in 0.5-m intervals, starting with $h_d = 5.5$ m where $f_e$ is zero and ending with $h_w = 0.5$ m where the edge of the channel is reached. For each interval of $h$, $f_e$ is determined from Figure 3, after which $\Delta L$ is calculated with (6) for each interval of $h$. The inflow for each increment of $\Delta L$ is calculated as the sum of the outflow and $f_e \times \Delta L$. The results of the calculations are shown in Table 1.

The inflow for the last increment (increment 10 in Table 1) is 277 m³/yr, which is the seepage per meter length of channel on one side of the channel. The total seepage loss for the channel due to water use by salt cedars in the floodplain is thus 554 m³/yr per meter length of channel on the assumption that the conditions on the other side of the channel are the same. A profile of the water table and the average evapotranspiration rates for each increment of $\Delta L$ are shown in Figure 4.

If the salt cedars are removed and the $f_e-h$ relation for the postremoval floodplain condition is known, the postremoval seepage can be computed. By assuming a certain postremoval $f_e-h$ relation (Figure 3) the total postremoval seepage from both sides of the channel is calculated as 164 m³/yr per meter length of channel. Thus the phreatophyte removal potentially would save 390 m³ of water per year per meter length of stream. The postremoval water table profile and corresponding $f_e$ distribution are shown by the dashed lines in Figure 4. Removal of the salt cedars caused a considerable rise of the water table.

Simplified procedure. If the relation between $f_e$ and $h$ is a step function, $f_e$ being constant at potential rate for $h < h_d$ and abruptly reduced to zero at $h_d$, the seepage from the channel can be calculated directly with (8), which for this purpose is written as

$$L^2 = \frac{K}{f_e} (H_w^2 - H_e^2)$$

(9)
In this equation, $L$ is the distance from the channel where the water table depth has reached $h_a$, and $f_e$ has become zero. The vertical distance between the water table and the impermeable layer at that point is $H_a$ (Figure 2). Since the seepage $Q$ per unit length of channel on one side of the channel is equal to $f_e L$, multiplying (9) by $f_e^2$ yields

$$Q = \left[ K f_e (H_w - H_a) \right]^2$$

(10)

The direct calculation of $Q$ with (10) is much simpler than the incremental procedure of (6) as exemplified in Table 1. If the $f_e-h$ relation is not a step function, $Q$ can still be directly calculated with (10) if the actual $f_e-h$ curve is replaced by an 'equivalent' step function. The height of this equivalent step function is equal to the potential evapotranspiration rate, which is $f_e$ at $h = 0$. The width of this equivalent step function is such that the area under the step function is the same as the area under the actual $f_e-h$ curve. Thus $h_a$ of the equivalent step function, referred to as $h_a'$ (Figure 3), is calculated as

$$h_a' = \int f_e dh / (f_e)_{h=0}$$

(11)

where $f_e dh$ is the area under actual $f_e-h$ curve, and $(f_e)_{h=0}$ is $f_e$ at $h = 0$, or potential evapotranspiration rate.

The validity of the equivalent step function approach is not readily proven mathematically but can be demonstrated by calculating $Q$ with the incremental procedure of (6) and comparing it with $Q$ calculated with the equivalent step function and (10). This was done for three widely different $f_e-h$ relations, namely, the sigmoid curve for salt cedar in Figure 3 and the hypothetical concave and convex curves in Figure 5. The channel and geological conditions were the same as those used for the example in Table 1 except that for the curves of Figure 5, $h_w$ was taken as 0.4 m instead of 0.5 m to facilitate the computations. The results (Table 2) show excellent agreement between the $Q$ values obtained with the different techniques, which supports the validity of the equivalent step function approach.

The equivalent step function approach cannot be used to calculate the water table profile and the corresponding $f_e$ distribution in the floodplain. Also the equivalent step function cannot be used if $h_a' < h_w < h_a$ because the equivalent step function would yield $Q = 0$, whereas the actual $f_e-h$ relation would indicate some evaporation from the water table near the stream.

**DISCUSSION**

Results of evaporation studies [Hellwig, 1973; Horton, 1973; Ripple et al., 1972; van Hytklama, 1970, 1974; Whister et al., 1968] indicate that possible orders of magnitude for $h_a'$ may be 2–3 m for salt cedars and similar deep-rooted plants, about 1 m for shallow-rooted plants, and about 0.5 m for bare soil (less for coarse sands). Such values of $h_a'$ could be used with (10) to estimate the reduction in water losses that could be obtained by phreatophyte control.

By taking different values of $h_a'$ (using a hypothetical range of 0.5–8 m) and assuming $f_e = 2$ m/yr, (10) was used to calculate $Q$ for the same channel geometry and geological conditions as those used for the example in Table 1. These $Q$ values were then used to calculate the percentage reduction in $Q$ by replacing floodplain vegetation with a certain $h_a'$ by a vegetation or bare soil with a lower $h_a'$. The results (Figure 6) show that substantial percentage reductions in channel seepage can be obtained only if $h_a'$ after removal is much less than $h_a'$ before removal.

The percentage reduction in seepage losses from a stream due to changing the vegetation in the floodplain to a condition with lower $h_a'$ also depends on $h_w$, on the assumption that $h_w$ is the same before and after phreatophyte removal. This effect is shown in Figure 7, which applies to the same case as that in Figure 6. The curves show that the percentage seepage reduction due to a certain change in $h_a'$ increases with increasing $h_w$. For example, reducing $h_a'$ from 3 to 2 m gives a 20% reduction in channel seepage if $h_w = 0.5$ m but a 43% reduction if $h_w = 1.5$ m. The actual water saving, however, can be expected to decrease with increasing $h_w$.

Zones with different types of vegetation, each with its own $f_e-h$ relation, can be included in the calculation of the seepage losses.

**TABLE 2.** Comparison Between $Q$ Calculated With the Incremental Procedure of Equation (6) for the Actual $f_e-h$ Curve and With the Direct Procedure of Equation (10) for the Equivalent Step Function

<table>
<thead>
<tr>
<th>Curve</th>
<th>$Q$ Calculated With Actual $f_e-h$ Curve, m³/yr/m channel</th>
<th>Area Under Actual $f_e-h$ Curve, m³/yr</th>
<th>$f_e$ at $h = 0$, m/yr</th>
<th>$h_a'$ of Equivalent Step Function, m</th>
<th>$Q$ Calculated With (10) and Equivalent Step Function, m³/yr/m channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sigmoid salt cedar curve in Figure 3</td>
<td>277</td>
<td>6.41</td>
<td>2.45</td>
<td>2.62</td>
<td>281</td>
</tr>
<tr>
<td>Concave curve in Figure 5</td>
<td>197</td>
<td>3.45</td>
<td>2.5</td>
<td>1.38</td>
<td>200</td>
</tr>
<tr>
<td>Convex curve in Figure 5</td>
<td>279</td>
<td>6.08</td>
<td>2.5</td>
<td>2.43</td>
<td>280</td>
</tr>
</tbody>
</table>

*This is $Q$ on one side of the channel only.*
Application of the procedure to a hypothetical stream and floodplain shows that replacing a deep-rooted vegetation with bare soil or shallow-rooted vegetation causes a rise in the water table of the floodplain. The percentage reduction in seepage losses from the stream by phreatophyte control is significant only if the depth from which groundwater can be removed by evaporation is much smaller after removal than before.

The percentage reduction in channel seepage due to phreatophyte control tends to increase, and the actual amount of water saved to decrease with increasing vertical distance between the floodplain and the water level in the stream.

**Fig. 6.** Effect of \( h_u' \) before and after vegetation control in the floodplain on the percentage reduction in seepage losses from the stream. The curve parameter indicates \( h_u' \) after removal (in meters).

**Fig. 7.** Effect of vertical distance \( h_w \) between water level in stream and floodplain on percentage reduction in seepage losses for various combinations of \( h_u' \) before and after removal of deep-rooted vegetation. The solid lines indicate preremoval \( h_u' = 8 \) m, the dashed lines indicate preremoval \( h_u' = 3 \) m, and the curve parameter indicates postremoval \( h_u' \) (in meters).

**CONCLUSIONS**

The reduction in seepage losses from a stream due to removing deep-rooted vegetation (phreatophytes) in the floodplain can be calculated if the relations between evapotranspiration and water table depth are known for the phreatophytes and for the condition of the floodplain after the phreatophytes are removed. An incremental procedure is developed to calculate the seepage reduction. Horizontal steady flow below the water table is assumed.

The incremental calculation can be simplified drastically if the actual curve relating evapotranspiration rate to water table depth is replaced by an equivalent step function with the same area under the curve. This step function gave the same seepage as the incremental procedure in several comparisons.

**REFERENCES**


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