Using the Hydraulic Properties of Zeolite to Grow Desert Willow—A Case Study to Rehabilitate Riparian Areas of Semi-Arid Environments

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Abstract: Plants in riparian areas are well known for their beneficial functions such as providing biodiverse habitats, maintaining water quality, and stabilizing streambanks. However, riparian plants are declining in semi-arid environments due to long-term drought, a decline in groundwater table, and an increase in soil salinity. A new technique using clinoptilolite zeolite (CZ) as a wicking material with minimum artificial irrigation to grow desert willow [Chilopsis linearis (Cav.) Sweet] under field conditions is introduced; desert willow is native to riparian regions of the southwestern United States. For this study’s experiment, desert willow seedlings were planted in boreholes filled with clinoptilolite zeolite (CZ) as a substrate and in situ riparian sandy loam soil (RS) as a control. The boreholes extended to the groundwater table at two distinctive depths, shallow (avg. depth = 1.21 m) and deep (avg. depth = 2.14 m). The plants’ viability was then assessed by measuring their midday water potential (Ψmd) as an indicator of water stress. There was no significant difference in Ψmd (p > 0.05) between the plants grown in CZ and RS (mean Ψmd = −0.91 vs. −0.81 MPa) where the groundwater was shallow and a significant difference (mean Ψmd = −0.75 vs. −2.03 MPa) where the groundwater was deep. The proposed method is promising as an alternative method for growing desert willow or other plants for riparian rehabilitation with no artificial irrigation. However, its effectiveness depends on groundwater being accessible at the base of the boreholes used for planting.

Keywords: stem water potential; desert willow; riparian; clinoptilolite zeolite

1. Introduction

Riparian zones can be defined as strips of vegetation near bodies of water (i.e., streams, rivers, lakes, and drainage canals, among other water bodies) and considered as one of “the most valuable ecosystems on the earth”, as stated by Singh et al. [1]. Many have described riparian zones as havens of biodiversity [2]. Riparian vegetation by a streamside serves multiple benefits, including but not limited to the moderation of the water temperature of adjacent water bodies in order to provide biodiverse habitats for terrestrial and aquatic species and their prey, maintaining water quality by reducing suspended solids and filtering nutrient inputs to the stream, and the stabilization of streambanks in order to reduce soil erosion [2–6]. Despite the beneficial role of riparian zones in sustaining a healthy environment for lakes, rivers, and canals, plants in these zones are slowly disappearing [1,7]. Their disappearances are, in part, related to prolonged droughts, the canalization of rivers and ephemeral water systems, declines in the groundwater table, increases in soil salinity, and biological invasion. To help reestablish riparian lands and prevent them from further decline, several methods have been implemented, which include seeding, stem cuttings, and propagation [8–11]. However, some of these methods can be labor-intensive and...
expensive, with little or no success [9], and require the availability of water for irrigation. A method that has shown some success in the riparian areas of the Rio Grande Valley in NM, USA, is the deep planting of tree stems [9]. Long stems from cottonwood trees were planted up to depths of 2.4 m. The deep planting technique ensured the plant roots were in contact with the groundwater capillary fringe to root and grow [11].

Although there is vegetation in riparian areas where the groundwater table is deep and capillary rise is insufficient, they can be susceptible to desiccation. A method has been proposed using clinoptilolite zeolite’s (CZ) hydraulic properties as a wicking material to grow plants [12–14]. However, the alleviation of water stress in riparian plants using zeolite as a wicking material to grow plants is not well understood. This study aims to utilize the hydraulic properties of zeolite to assess the impact of water stress on desert willow (*Chilopsis linearis* (Cav.) Sweet) when planted in zeolite-filled boreholes extended to groundwater. Desert willow plants are native to the warm, arid climate of the southwestern United States and northern Mexico. They are commonly found in dry washes and along riverbanks at less than a 1524 m height above mean sea level (a.m.s.l.), where underground water is available during the entire year [15–17]. While desert willow performs best in well-drained soils, plants can tolerate acidic and alkaline soil conditions and grow on most soils, including clay, loam, and sand [15,16,18]. Desert willow plants are well suited for many uses, such as controlling soil erosion when planted in groups and providing cover and food for wildlife and insects. They can also be used for riparian rehabilitation projects, horticultural purposes for their attractive beautiful blooms, and enticing hummingbirds, among others [15,16,18].

Natural zeolites and their geological formations have been documented in the literature [19–22]. Clinoptilolite zeolite (CZ) is a volcanogenic sedimentary mineral. It is composed primarily of aluminosilicates in a three-dimensional crystal lattice with loosely bound cations and can hydrate and dehydrate without altering its crystal structure [22]. Dung et al. [13] showed that CZ could be used as a wicking material to raise water to 1.5 m and as an amendment to sandy soils to improve their water retention properties. Piñon-Villarreal et al. [14] also tested the capillary rise of CZ and riparian soils in a field experiment and compared it with a simulation model using Hydrus-1D. The simulation coincided with field measurements and indicated that the application of CZ as wicking material could be used for sustaining native vegetation in dry environments, so long as the depth to groundwater table (DGW) remained shallow (<3 m).

This study measured the midday stem water potential (Ψ<sub>md</sub>) of desert willows planted in boreholes filled with CZ and those planted in riparian sandy loam soil (RS) during the growing season of 2016. It was hypothesized that: (i) the desert willows planted in boreholes filled with CZ under field conditions would exhibit less water stress than those planted in riparian sandy loam soils (RS), and (ii) the water stress in the desert willow would increase as the depth to groundwater table increased in both CZ and RS, but the stress would be more pronounced in RS.

2. Materials and Methods
2.1. Study Location and Experimental Setup

The study site was located within the Stanford Engineering Research Center for Reinventing the Nation’s Urban Water Infrastructure (ReNUWIt) riparian research Test-Bed at Sunland Park, New Mexico. The ReNUWIt Sunland Park Test-Bed covers an area of 9 hectares and is situated at the intersection of the Nemexas earthen drainage canal and the Rio Grande, near the border of Sunland Park, New Mexico, and El Paso, Texas (Latitude: 31°50′16.1″ N, Longitude: 106°36′36.8″ W, elevation: 1145 m above mean sea level). (See Figure 1).
The drainage canal starts near Chamberino, New Mexico and runs for about 35 km, intercepting irrigation drainage water, a high groundwater table at some locations, and flood runoff during rainfall events, and empties its water into the Rio Grande. The drain crosses underneath the Rio Grande at the study site by way of a 2.4 m diameter concrete culvert and eventually empties into the meandering part of the Rio Grande downstream on the El Paso, Texas, side. The site was cleared of a dense thicket of saltcedar (Tamarix ramosissima Ledeb. [Tamaricaceae]) and the topography of the land was altered to create a mild slope towards the canal for flood control.

The climate of the study site is typical of a semi-arid environment, where the average rainfall within the region is 200–230 mm according to Malm [23]. Most of the precipitation occurs from July through September monsoon season. The climate data by Malm [23] near the study site reported monthly minimum and maximum mean temperatures ranging from −3.3 °C to 34.5 °C, with, however, records of extreme high temperatures sometimes reaching greater than 37.8 °C.

The experiment design included two plots named DGW1 and DGW2, 83 m long by 24 m wide each. The plots were selected based on the depth to groundwater (DGW) from the ground surface, where the average DGW was 1.21 m for the DGW1 plot and 2.14 m for the DGW2 plot. The ground surface topography (i.e., elevation) was altered to achieve the two different DGWs. The DGW was monitored using 5.08 cm (2 inch) screened polyvinyl chloride (PVC) piezometers (Rodgers and Co., Inc., Albuquerque, NM, USA) installed in each of the plots. The electrical conductivity and pH of the groundwater were measured.
using the Sension™5 conductivity meter and model HQ30D pH meter (HACH® Company, Loveland, CO, USA).

The two plots were separated 12 m apart, as shown in Figures 1 and 2A. Two treatments of CZ (8 trees) and in situ riparian sandy loam soils (RS) (8 trees) were applied within each plot, with a total of 32 trees in the two plots. In DGW1, four plants in each treatment were staggered as RS-CZ-RS-CZ and in DGW2 as CZ-RS-CZ-RS. Sixteen boreholes were dug 4.6 m apart in each plot using a handheld auger with a 7.62 cm diameter until the groundwater was reached and then filled with CZ to within 30 cm below the ground surface (Figure 2). For the wicking process to work, it was ensured that the CZ was in contact with the groundwater with no air pockets within the filling material. Approximately 6 L of water was poured into the borehole until it was filled up to 30 cm below the ground surface. The top 30 cm of each borehole was then expanded to about 20 cm in diameter to accommodate the plant roots. The top 30 cm of the borehole was then backfilled with a mixture of CZ and RS at a volume ratio of 1:1 to inoculate inert CZ with in situ beneficial microorganisms (Figure 2B). The RS soil profile within the plots was determined as uniform based on multiple drillings using an auger to the groundwater table within the plots. The RS planting locations within each plot were left intact to reduce soil disturbance (compaction and porosity) and maximize the capillary rise under natural conditions.

Figure 2. Schematic illustration profile of: (A) desert willows planted in CZ-filled boreholes and riparian sandy loam soil (RS) within DGW plots; and (B) 3D profile view of Clinoptilolite zeolite (CZ) borehole profile surrounded by RS.
The CZ-filled boreholes were left for a week to let the water wick to the surface before planting. After a week, a hole was dug where the CZ and RS were mixed to accommodate the plant roots in the CZ-filled boreholes for planting the trees. Similarly, a hole of 20 cm in diameter and 30 cm in depth was dug for RS. The plants in RS were also separated by 4.6 m. The salt and sodicity of RS were checked by taking several soil samples and testing them at a certified laboratory (AgSource Laboratories, Lincoln, NE, USA). The AgSource Laboratory uses a 1:1 soil/water slurry method for electrical conductivity and a saturated soil paste method for sodium adsorption ratio (SAR). The average electric conductivity (EC) of RS collected from the top 60 cm of the in situ soil was 2.5 dS/m and its SAR was 4.4. Meanwhile, the EC was 0.95 dS/m, with an SAR of 1.48 for CZ (St. Cloud Mining company, Winston, NM, USA). The ECs and SARs were determined as acceptable for growing the desert willow plants [24].

The CZ used in this experiment was mined in the USA at Winston, New Mexico, by the St. Cloud Mining Company. The company classified the CZ following the ASTM D392 method as medium coarse with a mesh size of 14 × 40 (sieved through a screen size of 1.4 mm and retained on a screen size of 0.42 mm). The bulk density of CZ was 0.78 g/cm$^3$. Zeolite was purchased in 18.14 kg (40 lb) bags, with each bag containing a volume of 0.023 m$^3$. About 0.7 of a bag (0.015 m$^3$) was used for the deep boreholes (2.44 m) and 0.43 of a bag (0.01 m$^3$) for the shallow boreholes (1.51 m). All the boreholes extended to approximately 30 cm below the water table. A total of 10 bags of CZ, including minor spills and borehole size adjustments, were used for all the 16 CZ boreholes in the DGW1 and DGW2 plots. The cost per bag was USD 5.00, a total of USD 50 for the ten bags. The cost of CZ can be relatively inexpensive at a discount rate when purchased in bulk (i.e., $ USD/Ton). It is essential to note that the costs of USD 50 do not account for labor costs and the cost of transporting material to the field site. The total cost will, therefore, vary depending on the restoration project location.

Desert willow seedlings in one-gallon tree pots (10 cm × 10 cm × 36 cm) about 92 cm tall were purchased from Los Lunas Plant Material Center, Los Lunas, NM, USA, (LLPMC). The propagation of riparian plants at the LLPMC is described in detail by Dreesen et al. [25]. The tree pots with plants were dipped in water in order to empty the plants with ease without damaging the roots, and they were then placed in the holes and covered with dug soils. The soil surrounding the plants was compacted slightly and then irrigated with 20 L of water once a week for a month and then once a month for the entire growing season of 2015, until the plants were fully established. No irrigation or fertilizer was applied after all the plants were established. The plants had grown as bushes to about 1.4 m tall when the stem measurements started. In each plot, 4 out of 8 plants in CZ and in RS, respectively, were randomly selected for $\Psi_{md}$ measurements.

2.2. Stem Water Potential and Climate Measurements

Water stress in desert willows was monitored by measuring their midday stem water potential ($\Psi_{md}$). $\Psi_{md}$ is widely recognized as one of the most reliable physiological parameters for assessing the moisture status of plants [26–29]. Numerous studies have demonstrated that $\Psi_{md}$ serves as a superior indicator of water deficit due to its direct correlation with plants’ physiological changes [27,28,30,31]. Midday $\Psi_{md}$ is particularly sensitive to variations in a plant’s water status compared to other water status measurements [31], such as leaf water potential ($\Psi_{leaf}$) and predawn leaf water potential ($\Psi_{pd}$). $\Psi_{md}$ measurements are typically conducted at midday, when water demand and photosynthesis are at their peak. Prior to measurement, leaves are enclosed in foil bags while still attached to the plant for approximately 1 h. This process allows the water potential of the leaves inside the bag to equilibrate with the water potential of the stem by temporarily halting photosynthesis and water loss within the leaves [30,32].
The Ψ\textsubscript{md} of the desert willows was measured every 3 to 4 weeks from June through to November, when the leaves were fully expanded, until they were senesced using a pressure chamber (Model 1000 by PMS Instrument Co., Albany, OR, USA) following procedures described by Deb et al. \cite{30}. In total, 3 stems from 4 randomly selected plants were initially selected from each treatment (CZ and RS) within each plot (DGW1 and DGW2) and covered with 14 cm × 23 cm aluminum foil bags. As the number of stems from the selected plants decreased over time, only two stems instead of three were selected for the measurements. Leaflets inside the tightly secured aluminum bags were left for an hour to allow the leaf matric potential to equilibrate with that in the stem and stop transpiration. After one hour of equilibration, the stems were cut from the plants using sharp hand pruners and immediately placed inside the pressure chamber to measure the stem water potential. Compressed nitrogen gas was released slowly into the chamber until a drop of sap appeared on the edge of the shoot. The amount of pressure applied to the chamber at this point was recorded as Ψ\textsubscript{md}. All measurements were conducted between 1200 HR and 1400 HR Mountain Standard Time in mid-afternoon.

Weather data, including precipitation, ambient temperature, and relative humidity, were measured hourly by the Sunland Park weather station (Figure 1) in the study site. The demand for moisture in the air or vapor pressure deficit (VPD), the difference between the saturated and actual vapor pressure, was calculated following Allen et al. \cite{33} using air temperature and relative humidity. Evapotranspiration (ET) referenced to a short crop (ET\textsubscript{SO}) was calculated using the American Society of Civil Engineers (ASCE) standardized reference (ET\textsubscript{SZ}) equation \cite{34}. The ET\textsubscript{so} serves as a good indicator of the potential ET.

2.3. Statistical Analysis

Statistical analyses of the midday Ψ\textsubscript{md} were conducted using SPSS Statistics (version 28) software (IBM Corp., Armonk, NY, USA). The results from an analysis of variance (ANOVA) using the Tukey–Kramer Test \cite{35} for an unequal number of sizes were used to determine if there were any statistical differences in the Ψ\textsubscript{md} among the plants grown in the CZ and RS treatments and DGW1 and DGW2 plots at \( p < 0.05 \). A non-parametric test was also applied using the Mann–Whitney–Wilcoxon (MWW) method \cite{36}. This method compared the mean ranks from paired distributions of the Ψ\textsubscript{md} measurements from the CZ and RS treatments at \( p < 0.05 \). The MWW method was applied to provide additional confirmation of significant differences among the treatments and DGW plots.

3. Results

3.1. Climate

The climate of the region was drier than normal in 2016. The annual rainfall measured in the study site by the weather station was only 119 mm, or 60% of the average (200 mm) (Table 1). Of the annual rainfall measured, 57% (68 mm) occurred from July to September in the monsoonal season. The monsoonal season in New Mexico occurs during the summer months from July to September due to moisture coming from the Gulf of Mexico leading to local high-intensity storms, as described by Sheppard et al. \cite{37} and Malm \cite{23}. Very little or no rainfall (19% or 23 mm) occurred during the early part of the growing season (i.e., January–June). The warm months of May and June received a total of 5 mm only.

Most of the extremely high ambient temperatures in the study site occurred from June through to August. For example, the daily maximum ambient temperature from June to August exceeded 35 °C for a total of 29 days, with 9 days exceeding 40 °C (Figure 3). The average hourly temperature and relative humidity during the Ψ\textsubscript{md} measurements were 33.9 °C and 24%, respectively, with the hourly VPD ranging from 3.37 to 4.89 kPa. During June and September, the daily VPD ranged from 2.20 to 3.29 kPa, indicating ample demand for moisture in the air. The monthly ET\textsubscript{SO} ranged from 144 to 218 mm during the same period, peaking in the middle of the growing season and later declining as the season progressed (Table 1).
Table 1. Monthly maximum (T_max) and minimum air temperature (T_min), average monthly relative humidity (RH), average monthly vapor pressure deficit (VPD), potential evapotranspiration (ET_{SO}), and precipitation (Precip.) at ReNUWIt Sunland Park Test-Bed, NM, USA in 2016.

<table>
<thead>
<tr>
<th>Month</th>
<th>T_max °C</th>
<th>T_min °C</th>
<th>RH %</th>
<th>VPD kPa</th>
<th>ET_{SO} mm</th>
<th>Precip. mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>23.6</td>
<td>−6.9</td>
<td>55.54</td>
<td>0.73</td>
<td>55.8</td>
<td>2.3</td>
</tr>
<tr>
<td>February</td>
<td>30.3</td>
<td>−8.9</td>
<td>42.66</td>
<td>1.26</td>
<td>83.9</td>
<td>4.6</td>
</tr>
<tr>
<td>March</td>
<td>29.6</td>
<td>−1.5</td>
<td>35.45</td>
<td>1.61</td>
<td>140.4</td>
<td>3.8</td>
</tr>
<tr>
<td>April</td>
<td>31.7</td>
<td>−1.1</td>
<td>40.43</td>
<td>1.73</td>
<td>158.9</td>
<td>7.1</td>
</tr>
<tr>
<td>May</td>
<td>35.9</td>
<td>5.6</td>
<td>37.70</td>
<td>2.24</td>
<td>202.9</td>
<td>1.0</td>
</tr>
<tr>
<td>June †</td>
<td>41.1</td>
<td>12.3</td>
<td>39.79</td>
<td>3.05</td>
<td>218.0</td>
<td>3.6</td>
</tr>
<tr>
<td>July †</td>
<td>41.9</td>
<td>17.6</td>
<td>42.32</td>
<td>3.29</td>
<td>217.3</td>
<td>9.1</td>
</tr>
<tr>
<td>August †</td>
<td>38.6</td>
<td>15.1</td>
<td>53.79</td>
<td>2.20</td>
<td>174.6</td>
<td>24.1</td>
</tr>
<tr>
<td>September †</td>
<td>36.5</td>
<td>10.6</td>
<td>53.35</td>
<td>2.02</td>
<td>143.9</td>
<td>34.3</td>
</tr>
<tr>
<td>October †</td>
<td>33.0</td>
<td>5.8</td>
<td>49.31</td>
<td>1.89</td>
<td>110.3</td>
<td>0.5</td>
</tr>
<tr>
<td>November †</td>
<td>28.2</td>
<td>−6.5</td>
<td>50.74</td>
<td>1.08</td>
<td>76.5</td>
<td>2.3</td>
</tr>
<tr>
<td>December</td>
<td>25.1</td>
<td>−6.2</td>
<td>58.41</td>
<td>0.73</td>
<td>51.8</td>
<td>26.7</td>
</tr>
</tbody>
</table>

Total 1634.2 119.4

† Period of stem water potential measurement.

Figure 3. Daily maximum (T_max) and minimum (T_min) air temperature and precipitation (R) measured by Sunland Park weather station.
3.2. Groundwater

The daily mean depth to groundwater (DGW) during the $\Psi_{md}$ measurements ranged from 1.1 m to 1.6 m and 2.0 to 2.5 m in the DGW1 and DGW2 plots, respectively (Figure 4). The average DGW during the $\Psi_{md}$ measurements in DGW1 was 1.21 m and in DGW2 was 2.14 m. During the monsoon rainy season, which lasts from July to September, the DGW decreased due to rainfall infiltration, as shown in Figure 4. The EC of the groundwater ranged from 1.58 to 3.77 dS/m, with an average pH of 7.4.

![Figure 4](image-url)  
**Figure 4.** Daily mean depths from the ground surface to groundwater table measured in DGW1 and DGW2 plots. Precipitation is shown as bars.

3.3. Stem Water Potential

The $\Psi_{md}$ data were collected during the growing season from June through to November. The growing season in New Mexico starts in March and ends in November. The desert willow leaves started to emerge in late March, were fully expanded in June, and started senescing during the third week of November. The $\Psi_{md}$ values of the desert willow plants in CZ and RS measured in DGW plots 1 and 2 are shown in Figure 5.

The daily $\Psi_{md}$ means for the plants grown in RS in DGW1 were $-0.99$ and $-0.85$ MPa measured in June, and $-1.06$ MPa in July. In comparison, the daily $\Psi_{md}$ means for the plants in RS in DGW2 were $-1.82$ and $-2.25$ MPa measured in June, and $-2.43$ MPa in July. The plants in RS in DGW2 lost vigor and eventually died at the end of July, so no measurement could be recorded. No statistical differences in $\Psi_{md}$ using the Turkey–Kramer test were observed among the plants growing in the RS and CZ of DGW1 and CZ of DGW2 during the pre-monsoonal warm season (Table 2). However, a significant difference was observed in the plants growing in the RS of DGW2 (mean $\Psi_{md} = -2.03 \pm 0.170$ at
The daily \( \Psi_{md} \) means of the plants in the CZ and RS of DGW1 and CZ of DGW2 were low during the post-monsoonal season. Meanwhile, similar results were observed using a non-parametric test (Table 3). Paired distributions among the treatments indicated significant differences between RS2 and other treatments (i.e., RS1, CZ1, and CZ2, \( p < 0.001 \)). Some differences were also noted between treatments, such as RS1 versus CZ1 (\( p = 0.032 \)) and CZ1 versus CZ2 (\( p = 0.006 \)), which may be attributed to the slightly higher \( \Psi_{md} \) during August.

**Table 2.** Results from ANOVA using Tukey–Kramer Test on mean midday stem water potential, \( \Psi_{md} \) (MPa) for different treatments with corresponding depth to groundwater (DGW) plots.

<table>
<thead>
<tr>
<th>DGW Plots</th>
<th>Treatment</th>
<th>N Samples</th>
<th>( \Psi_{md} \pm SE ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DGW1: 1.21 m</td>
<td>CZ1</td>
<td>33</td>
<td>(-0.91 \pm 0.046 ) (^a)</td>
</tr>
<tr>
<td></td>
<td>RS1</td>
<td>50</td>
<td>(-0.81 \pm 0.029 ) (^a)</td>
</tr>
<tr>
<td>DGW2: 2.14 m</td>
<td>CZ2</td>
<td>45</td>
<td>(-0.75 \pm 0.032 ) (^a)</td>
</tr>
<tr>
<td></td>
<td>RS2</td>
<td>12</td>
<td>(-2.03 \pm 0.170 ) (^b)</td>
</tr>
</tbody>
</table>

Note: Letters \(^a\), and \(^b\) represent interaction between treatments. Same letters indicate no significant difference among treatments at \( p < 0.05 \).
Table 3. Results from non-parametric test using Mann–Whitney–Wilcoxon on mean midday stem water potential, $\Psi_{md}$ (MPa), for different treatments.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>N Samples</th>
<th>Mean Ranks</th>
<th>Z-Value</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CZ1</td>
<td>33</td>
<td>36.00</td>
<td>-1.847 *</td>
<td>0.032</td>
</tr>
<tr>
<td>RS1</td>
<td>50</td>
<td>45.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CZ1</td>
<td>33</td>
<td>28.36</td>
<td>-4.548 **</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>RS2</td>
<td>12</td>
<td>8.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CZ1</td>
<td>33</td>
<td>32.03</td>
<td>-2.499 *</td>
<td>0.006</td>
</tr>
<tr>
<td>CZ2</td>
<td>45</td>
<td>44.98</td>
<td>-1.301</td>
<td>0.097</td>
</tr>
<tr>
<td>RS1</td>
<td>50</td>
<td>44.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CZ2</td>
<td>45</td>
<td>51.87</td>
<td>-1.301</td>
<td>0.097</td>
</tr>
<tr>
<td>RS2</td>
<td>12</td>
<td>7.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RS1</td>
<td>50</td>
<td>37.31</td>
<td>-5.189 **</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>RS2</td>
<td>12</td>
<td>7.29</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Different symbols * and ** indicate significant differences between treatments at $p < 0.05$ and $p < 0.001$, respectively.

4. Discussion

The desert willows planted in CZ exhibited less water stress (less negative $\Psi_{md}$) than those planted in RS under field conditions, where the DGW fluctuated between 2 and 2.5 m, with an average of 2.14 m during the year. The CZ successfully wicked water to the roots of the plants and alleviated water stress during the warm and dry months of the season, with no artificial irrigation after the plant seedlings were established. The $\Psi_{md}$ measurements responded to the effects of soil moisture, air temperature, and VPD. Similar responses were also observed by De Swaef et al. [28] in young apple tree cultivars (Malus domestica Borkh. ‘Matsu’ and ‘Cox Organe’) and Deb et al. [30] and Othman et al. (2014) [31] in pecans (Carya illinoensis (Wangenh.) K. Kochl]. The VPD is a good indicator of the air’s dryness or the air’s ability to accept water vapor from evapotranspiration or precipitation. During the stem potential measurements between 1200 HR and 1400 HR, the ambient temperature averaged above 30 °C and the relative humidity ranged from 19% to 30% from June to August. Concurrently, the average VPD during the measuring period ranged from 3.37 to 4.89 kPa from June to August during the peak of the growing season, and then declined to a range from 1.37 kPa to 2.26 kPa as the season progressed. The plants growing in the CZ of DGW2 did not exhibit high water stress ($\Psi_{md}$ ranged from $-0.82$ to $-1.12$ MPa), despite a high VPD in the summer months (VPD ranging from 2.20 to 3.29 kPa), high evapotranspiration ($ET_{SO}$ ranging from 144 to 218 mm), and photosynthesis rates. This was primarily due to the availability of moisture wicked by CZ to the plant root zone.

In contrast, the plants in the RS of DGW2 exhibited high water stress exceeding $-2.75$ MPa. The soil was very dry (6% volumetric water content) due to low amounts of precipitation (12.7 mm from June to July). Eventually, the plants died from desiccation, since they could not access the groundwater. Meanwhile, the volumetric moisture content in DGW1 for RS was higher (15%) than in DGW2. The plant roots were within the groundwater capillary fringe, allowing them to survive.

According to Depree and Ludwig [38], during an excavation study at Jornada Bajada Site Desert Biome in New Mexico, the tap-roots of desert willow plants were observed to extend up to 1.6 m, with the highest percentages of root biomass (72%) observed in the topsoil layer from 0 to 0.4 m, 18% from 0.4 to 0.8 m, 8.6% from 0.8 to 1.2 m, and 1.4% at a 1.4 to 1.6 m depth. A high percentage of the root biomass in the topsoil layer subjects the desert willow plants to high evaporation loss from the topsoil, making them more vulnerable to desiccation. The desert willow plants in this study did not show water stress when planted in an area where the groundwater was shallow (i.e., 1.21 m). In this case, the use of CZ is not necessary, since the plants had access to the groundwater capillary
fringe and water table. An increase in the volumetric soil moisture content from 6% to 17.5% during the rainy monsoon season alleviated the stress in the plants. Those plants that survived in the CZ and RS of DGW1 and CZ of DGW2 continued to flourish and looked healthy when inspected visually. Clinoptilolite zeolite as a wicking material is promising for use as an alternative method to grow plants that are physiologically similar to desert willow (e.g., cottonwood (Populus fremontii S. Wats), black willow (Salix nigra Marsh.), giant sacaton (Sporobolus wrightii Munro ex Scribn.), and seep willow (baccharis salicifolia (Ruiz & Pav.) Pers.) in riparian or other restoration projects where the groundwater table is, at most, 2.5 m. The water stress in other plants growing in CZ, however, is yet to be tested.

Meanwhile, the mean \( \Psi_{md} \) values measured in the CZ and RS of DGW1 and CZ of DGW2 are comparable to those reported by Odening et al. [39]. Odening et al. [39] conducted a field study where the predawn water potentials (\( \Psi_{pd} \)) were measured for three plant species, including desert willow. They found that \( \Psi_{pd} \) values ranging from \(-1.4\) to \(-1.7\) MPa did not affect photosynthesis in the desert willow. The \( \Psi_{pd} \) reflects the plant water status after plants have recovered from the previous day’s conditions, but it does not reflect the water status during their maximum water demand, like \( \Psi_{md} \) [32]. However, the variability caused by light exposure and temperature is reduced by taking measurements at dawn. In a separate study, Odening et al. [39] exposed desert willows to a dry cycle (less watering) under the controlled lighting and temperature conditions of a greenhouse. They found that, at a relatively high water potential (\( \Psi_{pd} = -3.5 \) MPa), the net photosynthesis of desert willow stopped. In comparison, some plants in the RS of DGW2 experienced high water stress, with \( \Psi_{md} \) reaching up to \(-2.75\) MPa. They wilted and eventually died.

5. Conclusions

The application of CZ as a wicking material to grow desert willow plants in riparian sandy soils where DGW is shallow was assessed. As an indicator of water stress, the \( \Psi_{md} \) of the plants was measured. The CZ was able to supply water to the desert willow plants without irrigation where the DGW ranged between 2 and 2.5 m (average = 2.14 m). A slight fluctuation in DGW from 2.14 m did not make much difference in plant water stress (i.e., \( \Psi_{md} \)). However, the plants would eventually desiccate if a decline in DGW in this study was to exceed 2.5 m, because the CZ would lose contact with the groundwater table and cutoff the capillary rise. The desert willow plants in the RS of DGW2 did not survive at the same groundwater table (2.14 m) as in CZ. The success of utilizing CZ to grow plants is contingent on the groundwater availability at the base of the boreholes used for planting.


Funding: This study was financially supported by the Reinventing the Nation’s Urban Water Infrastructure (ReNUWIt) Engineering Research Center, Stanford, CA (NSF-Project EEC-1028968).

Data Availability Statement: The data supporting the conclusions in this article will be made available by the authors on request.

Acknowledgments: The authors thank the National Science Foundation Engineering Research Center for Reinventing the Nation’s Urban Water Infrastructure (ReNUWIt) award no. EEC-1028968 for funding this project and Elephant Butte Irrigation District (EBID) especially Gary Esslinger, Zachary Libbin and James Phillip King for their contribution and support to make this project successful. Our extended appreciation to Richard Lathy, Nirmala Khandan, Rolston St. Hilaire and Brent Tanzy for their guidance and support throughout this project. We thank St. Cloud Mining Company, especially Joseph McInaney for donating the CZ mineral used in the experiment. This project was made possible by the support and effort of the following students who assisted with the setup of the experiment: Ernesto Santillano, Cantekin Kivrak, Youness Bougteb, Ashley Jaramillo, Pablo Soto, John Miyagishima, and Garrett Gibson. Thanks to Kristina Macro from the State University of New
York (SUNY) College of Environmental Science and Forestry, Syracuse, New York, for helping with the data collection as part of her project and Bachelor’s thesis (Macro K., 2017, Hon. Thesis) [40].

Conflicts of Interest: The authors declare no conflicts of interest.

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