Assessment of drip irrigation sub-units using airborne thermal imagery acquired with an Unmanned Aerial Vehicle (UAV).

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Abstract

The proper maintenance of irrigation sub-units is a key aspect for efficient irrigation ensuring that theoretical high drip irrigation application efficiencies are achieved. The performance assessment methods are based on the discharge measurements of some emitters sampled within the irrigation unit. The emitter selection is a key aspect for guaranteeing that plot heterogeneity is well represented.

In this work, thermal images obtained by means of an Unmanned Aerial Vehicle (UAV) over an irrigation district were used to determine irrigation performance. Four irrigation sub-units were assessed with standard methods.

Canopy temperature showed a good correlation with the total flow discharge when plant water status variability in the sub-unit was high.

When standard irrigation performance assessment protocols are used, the sample of emitters is small and so the large existing variability might not be taken into account. Aerial thermal images can quantify plant water status in large areas enabling the detection of some failures in the irrigation delivery system that might not be always detected with the standard irrigation performance assessment protocols.

Keywords: Irrigation, thermal imagery, drip irrigation, performance assessment sub-unit, citrus.

Introduction

Drip irrigation is generally considered to be the most efficient irrigation system because it allows watering crops to be irrigated whilst reducing soil evaporation and maximizing plant transpiration, the productive component of any orchard crop water balance. However, drip irrigation systems are susceptible to possible malfunctioning because proper system maintenance of the irrigation sub-units is needed in order to ensure that, at the field level, the theoretical high drip irrigation application efficiencies are achieved.

Several methods have been proposed to assess the performance of drip irrigation sub-units.

The most popular method is the one proposed by Merriam and Keller (1978) which was adopted by FAO (1986). It is based on the discharge measurements of some emitters sampled within the irrigation unit. This sample is selected from four laterals located at
the inlet, at a third and two-thirds of the manifold length and the fourth at the
downstream end.
However, the emitter selection is a key aspect for guaranteeing that the plot
heterogeneity is well represented.
Other authors as Bralts and Kesner (1983), Bralts and Edwards (1986), Bralts et al.
(1987) and ASAE (1998) presented a statistical approach were 18 points were selected
at random to measure both their flow discharge and their pressure. According to Juana
et al (2007), from an operational viewpoint, the random selection of emitters is more
laborious than the Merriam and Keller approach, and measurement of pressures at
disperse points is not always easy.
In the Mediterranean area, irrigated plots are generally grouped in irrigation districts
consisting of several hundred irrigation sub-units receiving water from a collective
network. In these circumstances, it is very time consuming and expensive to carry out a
proper evaluation and maintenance of the entire irrigation system. Tools to identify the
water status of large irrigated areas would be desirable to remotely detect areas where
the irrigation system was not working properly.
Infrared thermography is a powerful tool to remotely determine canopy temperatures
($T_c$), which are often related to plant water status (Jones, 1999; Merlot et al., 2002;
Jones et al., 2002). Images can be taken by thermographic cameras carried on airborne
platforms (Berni et al., 2009). These images have sufficient spatial resolution to detect
individual tree temperature so allowing determination of the tree-to-tree variations in
plant water status (González-Dugo et al., 2012).
In the case of citrus trees under a coastal Mediterranean environment, Ballester et al
(2013) reported that canopy temperature ($T_c$) was a good plant water stress indicator
when midday air vapour pressure deficit (VPD) values were below 2.7 kPa and images
were taken from above the canopies. In those situations, deficit-irrigated trees had
higher $T_c$ than the controls, this difference being at most 1.7 °C when the stem water
potential ($\psi_s$) was -1 MPa lower in deficit-irrigated trees than in the well watered ones.
Our hypothesis is that high resolution canopy temperature maps can be used to assess
the tree-to-tree variations in plant water status of irrigation sub-units, as an aid to
improving the ground assessment of the irrigation performance of large irrigated areas
such as an entire irrigation district.

**Methodology**

**General overview of the irrigation district**
The irrigation district where the study was conducted was located in Picassent, in the province of Valencia (Spain, 39.38 N, 0.475 E). The total irrigated area was 310 ha. Water was delivered by means of two independent pressurized irrigation networks. Each network had an independent pumping group. Before water was injected, it was filtered by means of mesh filters. Collective fertigation was practiced.

Plots were irrigated by drip irrigation. 669 irrigation sub-units were connected to the network by means of 130 multi-outlet hydrants. Each sub-unit is composed of a main pipe called manifold, which feeds irrigation laterals with emitters. Each hydrant had a mesh filter. The plot average size was 3276 m². Citrus trees were the predominant cultivated crop.

**Thermal imagery acquisition and processing**

An area of 400 ha with 264 irrigated plots was overflown on 23 August 2011 at 10:00 GMT with an unmanned aerial vehicle (UAV) equipped with a thermal camera, acquiring imagery at 20 cm resolution. Images were georeferenced and atmospherically corrected to obtain surface temperatures. Images were subsequently processed to extract tree Tc, generating a raster dataset with the continuous canopy temperature of the entire orchard.

Each image had a relative temperature scale. Coincident with the flight, stem water potential (\(\psi_s\)) was measured with a pressure chamber (Model 600 Pressure Chamber, PMS Instrument Company, Albany, USA) following the recommendations of Turner (1981) in five trees over a total of 40 plots in order to estimate crop water stress. \(\psi_s\) was chosen as the true field determination of plant water status due to its sensitivity to water deprivation (McCutchan and Shackel, 1992).

The \(\psi_s\) data measured from each tree were related with the individual tree Tc extracted from the airborne imagery. The air temperature and VPD at flight time on the date of the flight were 31.6 °C and 1.89 kPa respectively.

**Irrigation sub-units assessment**

Four irrigation sub-units where there was a close relationship between tree-to-tree variations in \(\psi_s\) and Tc were selected for further evaluation of the irrigation performance. The manifold had emitter laterals on both sides. Emitter flows for 16 trees were measured in three sub-units (1, 2 and 4). In a fourth, larger sub-unit (3), 32 plants were measured. In all sub-units, trees were drip irrigated by two parallel pipe lines with a total of 4-10 emitters per tree and all were evaluated. Table 1 summarizes the main agronomic, geometric and hydraulic features of the assessed sub-units. Values of lateral length field are double because the manifolds in each sub-unit had laterals on both sides.
Table 1 Agronomic, geometric and hydraulic features of the assessed irrigation sub-units.

<table>
<thead>
<tr>
<th>Sub-unit</th>
<th>Crop</th>
<th>Planting distance (m²)</th>
<th>Ground cover (%)</th>
<th>Area (m²)</th>
<th>Perimeter (m)</th>
<th>Nº Trees</th>
<th>Lateral length (m)</th>
<th>Emitter distance (m)</th>
<th>Emitter type</th>
<th>Nº of emitters per plant</th>
<th>Nominal Flow(l/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clemennules</td>
<td>5x5</td>
<td>52.3</td>
<td>6247</td>
<td>337</td>
<td>253</td>
<td>32.36</td>
<td>1m</td>
<td>Integrated</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Clemennules</td>
<td>5x5</td>
<td>48.7</td>
<td>3484</td>
<td>252</td>
<td>138</td>
<td>37.30</td>
<td>1m</td>
<td>Integrated</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Clemensons</td>
<td>5x2.5</td>
<td>31.6</td>
<td>4228</td>
<td>266</td>
<td>279</td>
<td>35.32</td>
<td>0.6-1.25</td>
<td>Integrated/ Button</td>
<td>4-2</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>Orogrande</td>
<td>5x5</td>
<td>78</td>
<td>4280</td>
<td>272.24</td>
<td>147</td>
<td>45.38</td>
<td>1.25</td>
<td>Integrated</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

Sub-unit 3 had two different emitter laterals. One of them was an integrated drip line and the other one had button emitters. Terrain was flat in the four sub-units.

Figure 2 shows tree locations where emitter flow was measured (green dots) and the location of the manifold pipe in each irrigation sub-unit.

For each sub-unit, the coefficient of uniformity (CU) of flow emitter was calculated using the formula:

\[
CU = \frac{\bar{q}_{25\%}}{\bar{q}} \cdot 100
\]  

(1)

Where \(\bar{q}_{25\%}\) is the mean of the lower percentile 25 % (l h\(^{-1}\)) and \(\bar{q}\) is the mean of the sampled emitters.

According to Merriam and Keller (1978), sub-unit performance was classified as shown in ¡Error! No se encuentra el origen de la referencia.¡

Table 2 Classification of irrigation performance according to the coefficient of Uniformity values (CU).

<table>
<thead>
<tr>
<th>CU %</th>
<th>Performance classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 90</td>
<td>Excellent</td>
</tr>
<tr>
<td>80-90</td>
<td>Good</td>
</tr>
<tr>
<td>70-80</td>
<td>Acceptable</td>
</tr>
<tr>
<td>&lt; 70</td>
<td>Poor</td>
</tr>
</tbody>
</table>

Moreover, the total flow per plant (q\(_P\)) and the variation coefficient (CV\(_P\)) were calculated. The sub-unit performance CV\(_P\) can be classified as displayed in Table 3.

Table 3 Classification of irrigation performance according to the variation coefficient per plant (CV\(_P\)).

<table>
<thead>
<tr>
<th>CV(_P)</th>
<th>Performance classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 0.4</td>
<td>Unacceptable</td>
</tr>
<tr>
<td>0.4-0.5</td>
<td>Low</td>
</tr>
<tr>
<td>0.3-0.2</td>
<td>Acceptable</td>
</tr>
<tr>
<td>0.2-0.1</td>
<td>Good</td>
</tr>
<tr>
<td>&lt; 0.1</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

Finally, the tree-to-tree variations in the total tree water flow were compared with the tree Tc.
Results

Tc was compared to ψs in each irrigation sub-unit. The determination coefficients R² indicate that particularly in sub-units 3 and 4, Tc differences among trees of each irrigation sub-unit reflected real differences in plant water status. The R² values obtained were higher than those reported by Ballester et al. (2013) for zenithal images using a hand-operated thermographic camera. This difference might be because the air VPD at the flight date was 1.89 kPa, while in Ballester et al. (2013), VPD was higher varying from 2.3 to 4.5 kPa and they concluded that the relationship between Tc-ψs is weaker at high VPD values.

Table 4 From a sample of five trees for each assessed irrigation sub-unit obtained and the statistical significance of R². Tc values are relative for each irrigation sub-unit being 0 the coldest Tc pixel and Tc Max the Tc e of the hottest canopy pixel in the image.

<table>
<thead>
<tr>
<th>Sub-unit</th>
<th>Min ψs (MPa)</th>
<th>Max ψs (MPa)</th>
<th>ψs Range (MPa)</th>
<th>Tc Min</th>
<th>Tc Max</th>
<th>Range Tc</th>
<th>TcMax</th>
<th>R²</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1.44</td>
<td>-1.06</td>
<td>-0.38</td>
<td>1127</td>
<td>2554</td>
<td>1427</td>
<td>5039</td>
<td>0.47</td>
<td>0.19</td>
</tr>
<tr>
<td>2</td>
<td>-2.05</td>
<td>-1.30</td>
<td>-0.75</td>
<td>1476</td>
<td>5237</td>
<td>3761</td>
<td>6543</td>
<td>0.48</td>
<td>0.26</td>
</tr>
<tr>
<td>3</td>
<td>-2.33</td>
<td>-1.14</td>
<td>-1.19</td>
<td>2388</td>
<td>3419</td>
<td>1031</td>
<td>5417</td>
<td>0.95</td>
<td>0.07</td>
</tr>
<tr>
<td>4</td>
<td>-1.36</td>
<td>-1.00</td>
<td>-0.36</td>
<td>550</td>
<td>3276</td>
<td>2725</td>
<td>5157</td>
<td>0.55</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Table 5 shows the results of the performance assessment. The mean flow emitter q̄ and CU were obtained for each irrigation sub-unit. Two sub-units were classified as “good performance” as described in ¡Error! No se encuentra el origen de la referencia., and two units as poor due to the low CU (51.7% and 67 %). The low water flow uniformity in these two sub-units was due to inadequate filter equipment maintenance at the hydrants which led to emitter clogging. The classification performed takes into account only the uniformity of flow emitters and it is useful to characterize the hydraulic performance. However, from the agronomic point of view, it is important to characterize the total amount of water supplied per tree (qp), which was related to the corresponding Tc (Table 5).

Table 5 Results of irrigation performance analysis of the four selected sub-units

<table>
<thead>
<tr>
<th>Sub-unit</th>
<th>q̄ (l h⁻¹)</th>
<th>CU(%)</th>
<th>C1</th>
<th>qp(l h⁻¹)</th>
<th>CV₁ₚ</th>
<th>C2</th>
<th>R²</th>
<th>Sig</th>
<th>CV_Tc₁ₚ</th>
<th>CV_Tc_Tot</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.47</td>
<td>89.44</td>
<td>Good</td>
<td>42.72</td>
<td>0.1</td>
<td>Excellent</td>
<td>0.01</td>
<td>0.85</td>
<td>0.18</td>
<td>0.34</td>
</tr>
<tr>
<td>2</td>
<td>4.59</td>
<td>84.76</td>
<td>Good</td>
<td>35.41</td>
<td>0.35</td>
<td>Low</td>
<td>0.49</td>
<td>0.024</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>3</td>
<td>3.49</td>
<td>51.75</td>
<td>Poor</td>
<td>16.11</td>
<td>0.33</td>
<td>Low</td>
<td>0.74</td>
<td>0.00</td>
<td>0.36</td>
<td>0.29</td>
</tr>
<tr>
<td>4</td>
<td>4.09</td>
<td>67.05</td>
<td>Poor</td>
<td>31.98</td>
<td>0.2</td>
<td>Acceptable</td>
<td>0.69</td>
<td>0.02</td>
<td>0.15</td>
<td>0.41</td>
</tr>
</tbody>
</table>

In Sub-unit 1, no relationship between Tc and qp was found probably because in this plot there was not enough variation in plant water status since the range of observed ψs was very small (0.38 MPa), and probably Tc did not allow detecting small differences in plant qp and plant water status. In the rest of the sub-units, better relationships were obtained between Tc and qp R². As an example, Figure 1 shows the relationship between Tc and qp for sub-unit 3.
Figure 1 Coefficient of determination (R²) between canopy temperature (T_c) and flow per plant (q_p, l h⁻¹) in Sub-unit 3. T_c units are relative with 0 for the coldest canopy pixel value and 5417 for the hottest pixel.

The classification, according to CV_p, showed only one sub-unit with excellent performance (Sub-unit 1), another one with acceptable performance (Sub-unit 4) and two with low performance (Sub-units 2, 3).

Sub-unit 2 was classified as good in C1 but was considered low in C2. CU can be good due to a good hydraulic performance, but this does not necessarily imply that flow uniformity per plant is high. As it is shown in Figure 2, sampled trees located in the lateral extreme have higher T_c than most of the trees (noted in as Incidence 1). Because the emitter laterals were not long enough and did not reach the end of the plot, trees at the end of the line had less emitters than trees placed in the middle of the lines. As a consequence, the irrigated wet area was smaller for trees located at the end of the plot and also were submitted to higher radiation regime because they were located at the end of the plot.

Moreover Sub-unit 2 had two emitter laterals completely clogged as can be seen in Figure 2 noted as Incidence 1. These types of failure can be easily detected by the thermal images. On the other hand, they might not be detected with the standard irrigation performance assessment where only a sample of irrigation emitters can be evaluated.

Sub-unit 3 had bad performance for C1 and C2 classifications. Moreover a failure was detected in an emitter lateral because it was clogged (noted as incidence 3 in Figure 2). Pressures at the beginning of this lateral (63 kPa) and at the downstream end (60.3 kPa) were quite low compared with the rest of the sub-unit laterals (a mean of 110 kPa and 94 kPa). Consequently flow discharge was lower than in the other laterals.

Sub-unit 4 was classified as acceptable according to C2. However, CV_{T_c,s} is rather different from CV_{T_c,Tot}. That means that the sampled trees are not representative of the total variation in the population. Incorrect agronomic design was detected in this sub-unit as shown in Figure 2 (noted as 2).
Figure 2 Thermal images of continuous tree canopy temperature ($T_c$) of 0.2 m spatial resolution overlapped over an orthophoto of 0.5 m spatial resolution. Intense red represents the hottest pixels and intense green the coldest pixel. Each image has its own scale temperature. The locations of the sampled trees and tertiary pipes in each assessed irrigation sub-unit are shown.

Conclusions
Thermal imagery can be used as a tool for helping assess irrigation sub-unit performance since canopy temperature is related to the flow discharge. The spatial variability of the temperature sub-unit map can help to make a diagnostic of irrigation performance before a field evaluation is conducted. In addition, the use of crop canopy temperature maps will help to select the most representative areas to sample for ground measurements of the irrigation system performance. The use of aerial thermography can help to redefine current protocols used for evaluating sub-units in order to assess correctly the sub-unit performance.
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