Importance of spatial information in irrigation management

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Abstract. Soil water tension is a widely used parameter to manage irrigation. The collection of simultaneous information on soil water tension from many locations in a field is now made possible through wireless tensiometers. Such automatic spatial data collection results in a better assessment of the field-average tension. Additional gains in water management efficiency can be obtained if some spatial patterns can be identified which represent zones large enough to be irrigated independently. When such conditions exist, excess water is often applied if subzones of high variability are not independently managed. In this case, important excess water and energy may be used. Hence, important water savings can be obtained by recognizing spatial variability patterns in soil water tension and managing such patterns as sub-units instead of as a whole field. This paper summarizes observations obtained from different studies investigating the presence of independent zones and their effect on irrigation needs.

Keywords: tensiometer, wireless, spatial variability, precision irrigation,

Tools for measurements of plant and soil water status

Irrigation water accounts for about 2 / 3 of drinking water consumption on the planet and irrigated areas increase year after year in order to improve overall land productivity. Adequate irrigation management remains an important factor for many crops, as any water application excess leads to energy waste. In general, with appropriate irrigation management, there is increased growth, reduced production times, a more efficient use of fertilizers and pesticides, and reduced water and nutrient losses to groundwater (or to runoff). Finally, there is a decreased risk of developing certain foliage and root diseases.
Various tools exist to manage water (Table 1). Atmospheric, plant and soil based measurements do exist. Timers can also be used.

Timers are very basic and generally do not add the appropriate amount of water. The cost is low, but for more precision the preference has been to control the application of water based on the amount of water evaporated and transpired by

Table 1 : Different tools used to evaluate water status

Measurement level		Plant	Atmospheric	Soil
Type of measurements	direct	Yield Photosynthesis Xylem potential		Matric potential
	indirect	Temperature Fluorescence	Evapotranspirative demand (ETP)	Water content

the plant [evapotranspiration (ETP)]. This involves estimating how much water to apply to the soil according to meteorological parameters such as temperature, net radiation, wind speed, the stage of growth. These data can be calculated from public software, mathematical formulas on Excel or forecasting weather stations. This approach is widely used in North America, although some authorities now require the addition of measurements in the soil to increase accuracy.

The ETP approach goes one step further than timers by trying to estimate the appropriate amount at the field scale. Although a very significant improvement over timers, it does not sense, however, the real need at the plant level at a particular site. Hence, despite the fact that irrigation can be recommended from atmospheric measurements, sufficient storage of water may already exist and water may be applied in excess. Also, ETP recommendations provide an assessment on a large scale but do not provide any information on local irrigation needs.

Therefore, a better assessment, at the plant or at the soil level would be provided by multiple measurements taken at the plant or soil level. Plant measurements (photosynthesis, stomatal conductance, leaf temperature, xylem potential) are widely used in research. However, for field applications, they remain expensive and required highly skilled people to operate the equipment and interpret the results. While still viewed as promising (Jones, 2004), they remain limited to research applications; however growers tend to rely more on soil-based measurements, which are easier to use and interpret.

Among the measurements taken in the soil, it has long been recognized that measuring matric potential (or water tension) is preferred as it is regarded as the best direct measure of water availability to crops (Van Pelt and Wierenga, 2001). It is more directly related to uptake than soil water content, since the tension is a measure of the ease with which water can be withdrawn from the soil by the plant. Matric potential determines the amount of water transpired, according to the principles of thermodynamics, in the absence of the significant effects of salinity. When the ground dries, that is what the plant "sees". As the water tension increases (the plant may begin to suffer) while its water content is lowered. The tension reference value for initiating irrigation is fairly well known and published values for different soil types and irrigation methods can be found (Werner, 2002). However, tensiometers do have problems as they require maintenance and calibration, which has sometimes limited their use in the field.

With respect to water content, advances in time (TDR) and frequency (FDR) domain reflectometry have renewed interest in using soil-based measurements to manage irrigation. Measuring water content requires specific soil calibration because the water content observed at the critical tension set point will vary with soil properties and the soil salinity (for FDR and capacitance probes). Moreover, the differences between the dry (start of irrigation set point) and the wet (stop) are very small in coarse soil (sand, structured clay and organic soils) and a very high accuracy is needed, which cannot be obtained with all water content probes.

Whatever type of approach is used (measuring soil water content or water tension), these approaches have shown performances superior to those based on evapotranspiration or on visual inspection to manage irrigation in the greenhouse and/or in field. This has lead to significant water and energy savings. In the future we expect to see the proportion of measurement tools in the soil increase. Moreover, some sensors can be combined with wireless transmission systems to yield real time data originating form different spatial locations.

In the near future, as was the case in precision agriculture, these tools will be used at different locations in the field to estimate local irrigation needs. In the United States, this approach has been termed "hydrozoning". By obtaining information about the spatial distribution of soil water tension, as well as additional measurement like salinity, soil oxygen content and temperature, significant gains in productivity and irrigation efficiency are to be expected.

The main problems associated with tension measurements are the small volumes of soil that are measured (an advantage with drip irrigation), the need to fill the tensiometer with water if the soil gets too dry, and the need to calibrate the equipment for the water height within the tensiometer. Moreover, an additional limitation for collecting spatial information data is the need to scout (physically read) the systems at regular time intervals. Several companies nowadays have introduced wireless communication systems that can be installed in the field to transmit data in real time using radio frequency units. Real time transmission of data using wireless tensiometers with reduced maintenance now exist. They allow real time collection of tensiometer data to properly manage irrigation.

This new possibility raises new questions: how many tensiometers do we need and where should we place them? The first obvious response is based on the number of crops to be managed, their growth stage, the existence of different irrigation zones and the influence of topography. For the same crop and within a same irrigation zone, two questions remain: where should they be located and how many of them should we use?

Where should the tensiometers be located? The answer varies: it really depends on spatial variability. We need to know whether or not the tension varies in a soil, if the variability of these zones is important, and if the variability is caused by differences between patches of uniform properties (in which case the variability is manageable if these zones can be grouped into adjacent subzones).

Field studies have indicated important variability in irrigation needs based on soil parameters and that of irrigation dosage (Warrick and Gardner, 1983). Additional information is also needed on local plant water uptake (Cyr, 1990). Therefore, adequate estimation of local irrigation needs should be based on real time data, as it allows for the integration of irrigation distribution uniformity, local drainage and storage properties and local effect related to plant water uptake. Abundant data can be found in the literature on water content and have shown the existence of patches and the persistence of these patches in time (temporal stability).

Little data exists for water tension (Van Pelt and Wierenga, 2001). These authors have shown though the temporal stability of such measurements at different locations in the field. Additional information on spatial distribution of water tension is illustrated in the cases below.

Case 1: Spatial variability in a potato field. Data were collected in the summer of 2007, at thirty different locations, from May to October. Soil water tensions were collected using wireless tensiometers every five minutes, at the 15 cm depth (30 cm once hilling was performed) for the whole duration of the experiment. Nitrate contents were collected at different periods and depths in the profile, at a total of 30 different locations.

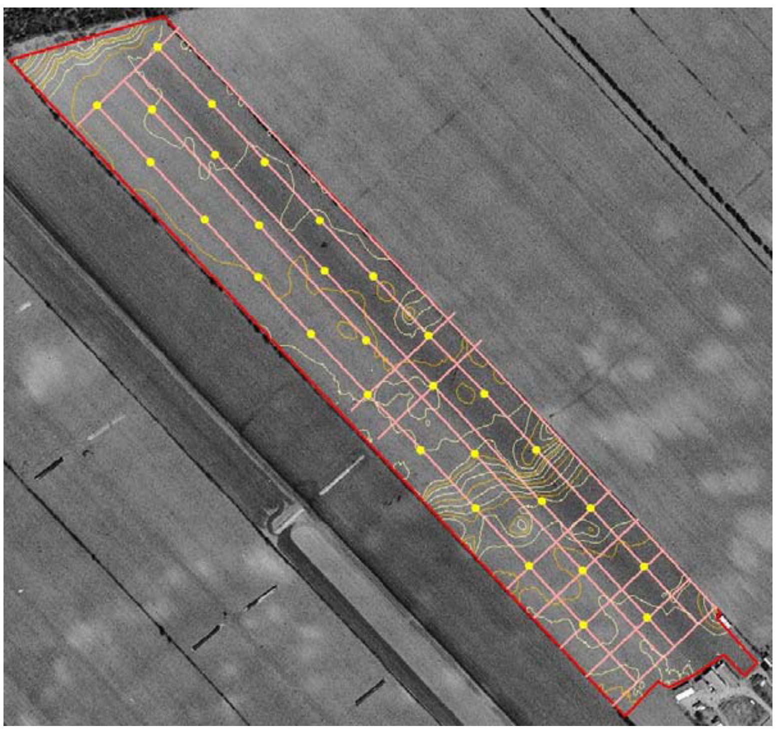

Figure 1. Position of the 30 different tensiometers and soil samples, in a 20 ha potato field along with the topographic lines

Patterns were observed in the interpolation maps. They confirmed the presence of a spatial structure for soil tension, zones being grouped into sizes about 250 m long (Figure 2). These zones were constant in time, with drier areas (on the higher surfaces), more humid areas in depressions and a wet spot in the bottom right corner (Figure 3). These patterns were directional and were longer in the direction of the slope. This meant that the similarity in tension was closer along than across the slope, an effect that might be due to tillage which tends to smooth out differences over time, since ploughing may be moving particles in the direction of the slope. The pattern also corresponded to the fact that the irrigation was carried out in four distinct zones, separating the field in four sections of equal size.

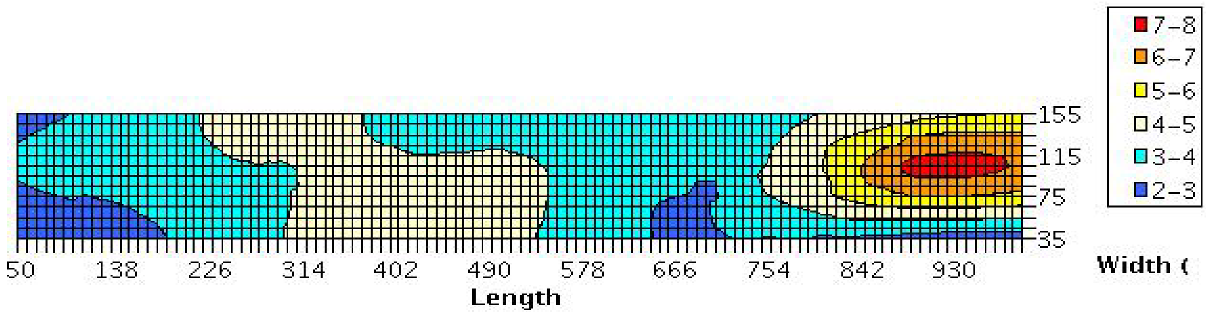

Figure 2. Mapping of the different zones for soil water tension during the wet period (in kPa or cbars)

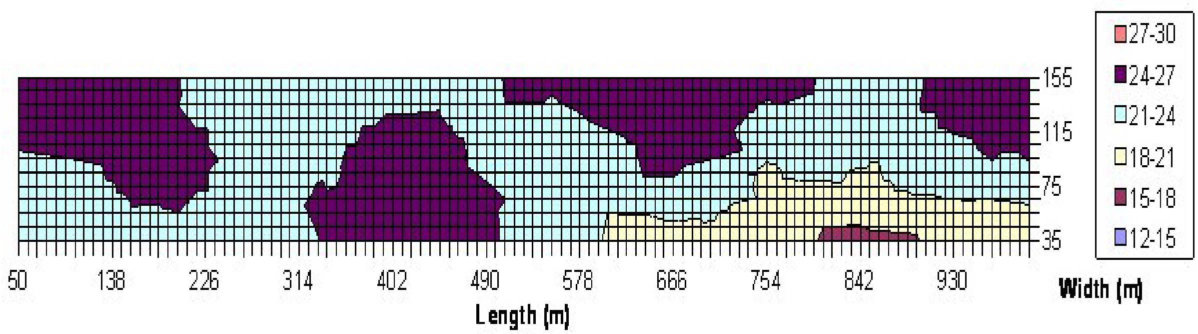

Figure 3: Mapping of different zones for marketable yields (T ha^{-1}).

Similar results were observed for potato yields (Figure 3). A positive and significant correlation was observed between potato yield and tension during wet events (Figure 4), suggesting that the yield decreased with decreasing tension (wetter soil). This correlation was consistent with similar behavior observed for cranberries (Bonin, 2008) and most likely occurred because the grower tended to over irrigate in the bottom right corner of the field, which most likely increased nitrate leaching. In this case, at least a quarter of the whole area was found to be over irrigated, resulting in net yield decreases. The results indicate that most of the irrigation could be largely reduced in that zone, hence generating about a 20-25% savings in water. Experiments are ongoing to confirm this conclusion.

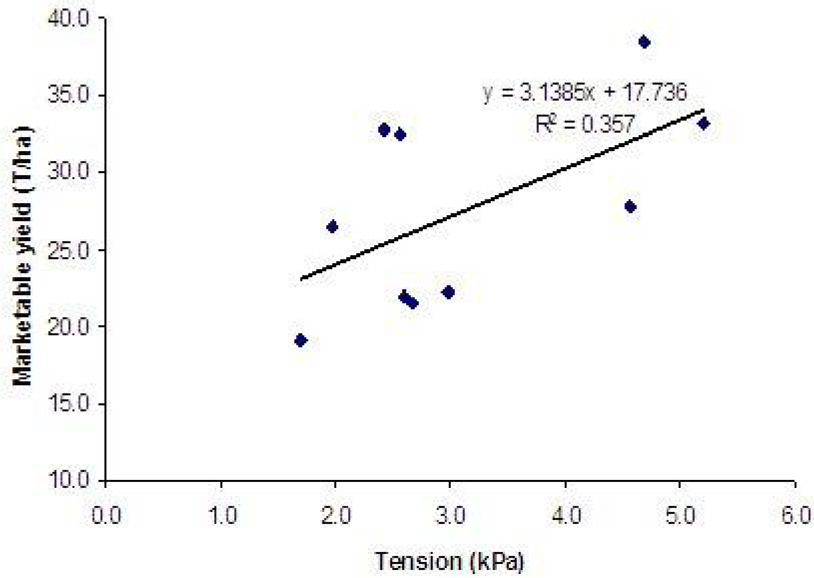

Fig. 4. Relationship between soil water tension during the wet period and potato marketable yield.

Case 2: A cranberry field. The second example came from a farm instrumented for three years with tensiometers (one per three fields), having a total of 60 fields. Preliminary measurements indicated a consistent spatial pattern of dry and wet zones in these fields and a relationship could be established between water tension during wet periods and crop yields (Figure 5).

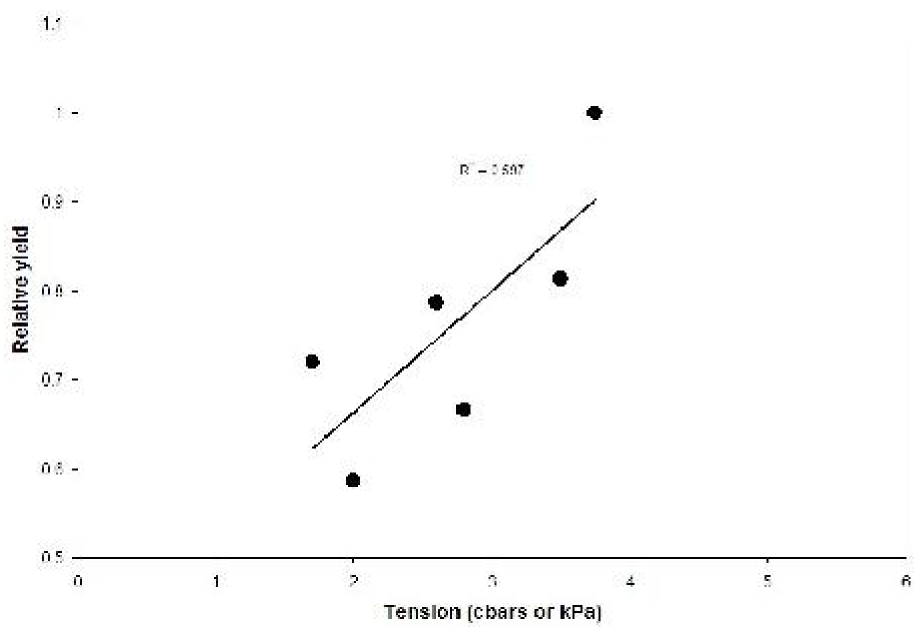

Figure 5. Soil water potential and cranberry relative yield.

Tensiometers were installed at the 8 cm depth, over an area of about 1.5 km^2. They were left to equilibrate for a total of two days and measurements were recorded within 2 hours at the end of May. Additional details can be found in Bonin (2008). Like the potato results, the data indicated the presence of a spatial structure, i.e., the data were not random. Hence, contour maps for water tension were generated by kriging, a statistical data approach found appropriate for regional (non random) variables. From this map, patches of low and high water tensions were observed that were consistent with observations made by the grower, with zones of about 400m in length showing changes in tension (Figure 6). This should be expected as it corresponded to the average length of a field, with each field being more or less independent of its neighbors. Indeed, each field has its own drainage and irrigation system. These differences were large enough though to have a significant effect on cranberry yield (Figure 5) and helped the farmer to assign different irrigation zones. Later work showed that one third of the fields gave the same yield with no irrigation at all, generating water savings of about a third relative to previous practices at the whole farm scale

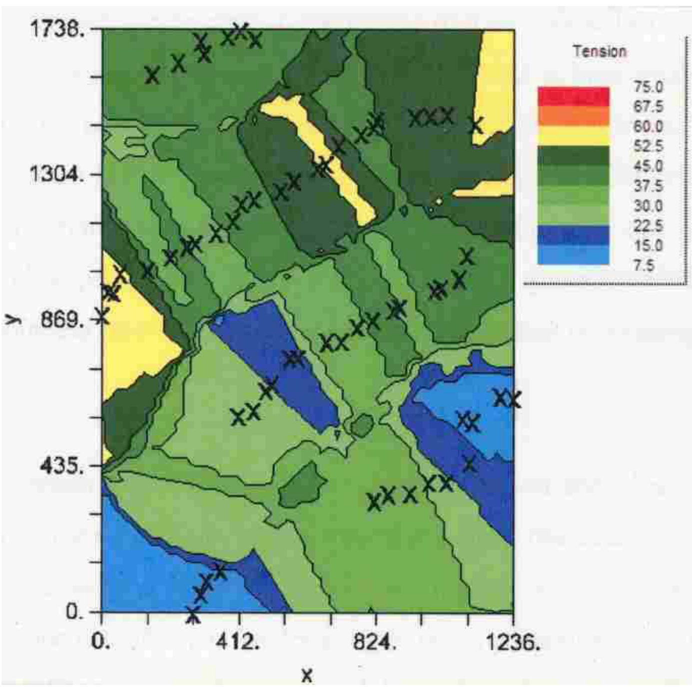

Figure 6. Tension variation (in mBars or hPa) found in 60 cranberry fields at the end of May.

Case 3. The Greenhouse case. The data were taken from Cyr (1990). They investigated the variation in water tension from a plastic greenhouse tomato experiment by taking tension measurements prior, between and after irrigation, for a total of 36 tensiometers. The tensiometers were located at 36 different locations within a Latin square design. Measurements were performed on actively growing plants over a full month period in the fall. Obviously, measurements that were carried out after irrigation were less variable than those measured before irrigation, but again, the data showed spatial variations that were stable in time, over the whole course of the study.

Their data clearly indicated that most of the variation (evaluated by calculating the standard deviation of the water tension) was observed for tensions between plants and then between the different patches found in the greenhouse (location). Measurements errors were found to be small relative to the other two sources of variability (Table 2). After irrigation, the standard deviation was the same between locations as that between growing slabs.

Table 2. Summary of the variation (standard deviation) of tension, in cm of water (1 cm=0.1 cbars)

Effect	Before irrigation	After irrigation
Location within the greenhouse	4.5	3.8
Between growing slabs within the same location	9.0	3.8
Measurement error	2.1	0.8

The pattern was expected to show more local variation than field data as growing slabs are truly independent when compared to soil zones. Therefore, little water redistribution should occur between growing slabs. In terms of water savings in a greenhouse operation, efficient leaching is critical. In this case investigations have shown that with 5 tensiometers within a greenhouse, instead of 1, the proportion of growing slabs efficiently leached goes from 8% to 31%. Because adequate leaching is performed, better growth is often observed and this leads to an improved water use efficiency of about 14% (Lemay, 2006).

How many tensiometers should we use? From all three examples, it becomes obvious that patches of large sizes exist in a different kind of growing environment and that they should be grouped and managed separately. Now, the second question remains. Once you have identified humid and dry zones, which are temporally stable, how many sensors should you used to detect those zones? From a purely statistical point of view, the answer is related to the maximum yield differences we can have between dry and wet zones. In both the greenhouse and field experiments, relationships can be drawn between tension and crop yield (Figures 4 and 5). Then a calculation can be carried out to determine the number of tensiometers needed in a zone. Obviously, the conclusions are site specific as they are dependent on the soil, irrigation distribution uniformity, type of crop and the expected tension effect on crop yield on top of the economical constraints linked to the cost of establishing and managing a new zone.

Case 1. The potato field. At least some calculations can give an indication and can be compared with the common statement made that 3 tensiometers in a zone should give a good estimate. For potatoes, calculations were based on the fact that a decrease of tension of 2 kPa would result in a yield drop of 20%. Then, we based the calculation on a T-test where

$$T = \frac{differences\ between\ two\ zones}{(SD * (NuT)^{1/2})}$$

where *SD* is the standard deviation and *NuT* , the number of tensiometers. This clearly suggest that at least 4 tensiometers per zone would be required in that field.

Number of tensiometers	T value	Probability level		Significance
		5%	10%	
2	2.00	12.70	6.31	Non significant
3	2.45	4.30	2.92	Non significant
4	2.83	3.18	2.35	Significant (10%)
5	3.16	2.77	2.13	Significant (5 and 10%)

Case 3. The Greenhouse case. In this case, real data were used to generate, using a Monte Carlo simulation, the effect of the number of tensiometers on the proportion of the total tomato plants of the greenhouse suffering from water stress (Table 3). The effect on yield is then expected to be very direct, as wilted tomato plants also show important yield losses due to blossom end rot. Obviously, growers will tend to over irrigate to avoid having stresses, resulting in more water and fertilizer use. It is clear in Table 3 that an adequate number of tensiometers could help avoiding over leaching, but it would require at least 3 tensiometers with a zone to reduce the percentage of stressed plants from 63% down to 33% and 5 tensiometers to reduce them to 15%.

Table 3. Results of Monte-Carlo simulation on the effect of the number of tensiometers on the percentage of greenhouse tomatoes plant showing sign of water stress.

Number of tensiometers	Percentage of the tomato plants suffering water stress
1	63
3	33
4	23
5	15

Conclusions

- With the coming of wireless technologies, soil tension measurements collected in real time at different location within fields or greenhouse make new information on the spatial and temporal distribution of this parameter available.

- All examples clearly indicated that the spatial patterns of large size (patches of same tension value) could be identified in all three examples and those patterns were constant in time, consistent with results of van pelt and Wierenga (2001) for soil tension and those of others for soil water content.

- Recognizing those zones and managing them individually could lead to important water savings (field case) or to an improve water use efficiency (greenhouse case).

- Results suggest that at least 3 tensiometers per zone are needed to detect a 20% yield drop 90% of the time in the potato field or 5 to detect 20% yield drops 95% of the time. For greenhouse operations, a minimum of 5 tensiometers per zone is necessary to have less than 15% of the greenhouses with less than 10% of the tomato plant in water deficit without detecting it.

- Recognizing those zones has lead to water saving up to about 30% so far.

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