Development of a recording water flow meter using ultrasonic measurement of water levels in a slotted U-pipe

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ABSTRACT

The accurate measurement and recording of water flow rates is necessary in the perfor-mance of field experiments in irrigation, overland flow or drainage studies. There is a lack of reliable, low-cost commercial flow meters that are able to operate under "non-pressure" conditions. This work describes a simply designed recording meter based on the ultrasonic measurement of water levels in a slotted U-pipe. A three-width slot design allows accurate flow measurements in the range 0–3 L s^{-1} and the ultrasonic probe allows for high resolu-tion measurements. Six replications of the instrument have been performed and calibrated (water levels against water flows) in laboratory experiments. After that, they have been successfully tested under field conditions, monitoring water flows which were recorded by using a data logger in the drainage system of an experimental farm in southwest Spain during several irrigation episodes in summer 2005.

Keywords:
Flow meter
Flow recording
Drainage waters

1. Introduction

Efficient management of water in agriculture production is necessary for economic and environmental reasons. The accurate measurement and recording of water flow rates is a relevant question in the performance of field experiments where soil drainage is a significant factor in the evaluation of water and nutrient losses (Dury et al., 1996; Gilliam et al., 1979), their potential environmental impacts (Skaggs et al., 1994; El-Mrabet et al., 2003), or in studies on water and salt balance (Su et al., 2005).

A large variety of flow meters are available for pressured pipes, including ultrasonic meters, venturis, flow nozzles, turbine meters, magnetic flow meters and v-cone meters. Nevertheless, drainage pipes usually operate under "open channel" conditions, and there is a lack of reliable, non-expensive commercial flow meters that are able to operate under these conditions. The scientific literature reports the use of drop-box weir systems (Johnson et al., 1966), tipping bucket (Khan and Ong, 1997), and the pumping of collected drainage water in combination with a flow meter for pressured pipes (Kanwar et al., 1988). Most recently, Novak et al. (2003) monitored subsurface flow at 10 min interval with a flow meter attached to a SIGMA-900P-Max autosampler; and Appelboom (2004) simultaneously measured water level (with a ceramic based pressure transducer) and velocities, using a STARFLOW® Doppler flow meter placed in the outflow pipe.

This work describes a simply designed recording meter based on the ultrasonic measurement of water levels in a slotted PVC U-pipe coupled to the outfall drain. It can produce

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Abbreviations: CV, coefficient of variation; PVC, polyvinyl chloride; dc, direct current records with high resolution, working under "open channel" conditions. A three-width slot design can be adapted to provide flow measurements in the desirable operation range. A range of 0–3 L s^{-1} has been selected in this work, based on the expected water discharge from tile drains in an experimental farm in southwest Spain. Thus, previous manual measurements indicated that each drain tile had outflows of as much as 1.7 L s^{-1} under a furrow irrigated cotton crop. Flow rates of 0–0.5 L s^{-1} were measured for sugar beet under sprinkler irrigation.

Six duplications of the instrument have been constructed and calibrated (water levels against water flows). They were then tested in field conditions. A data logger was used with these instruments to monitor the flow rates from the drainage system on the experimental farm. These measurements were taken during several irrigation events in the summer 2005.

2. Materials and methods

2.1. *The flow meter*

A PVC pipe with a U shape is connected to the outlet of the drain tile, with the U facing up (see Fig. 1).

A three stage rectangular slot in the free branch will allow the water to flow out of the pipe. In normal operation (see Fig. 2), the slot will only be partially covered by the water level inside the pipe. As the flow rate increases, the water level inside the U-pipe will also increase and consequently, the water discharge through the slot. An ultrasonic level sensor is located at the top of the slotted pipe to measure the distance to the free water surface. Once a calibration relationship is determined, the sensor signal can be related to the water elevation, h (measured above the base of the first slot).

A theoretical relationship can be established (Bernouilli's theorem) between the water level, h, and water flow, Q. An empirically determined coefficient is required to account for the contraction effect in the outgoing water stream. The width of the slot is designed to increase resolution, because thinner slots require larger changes in h for a given change in Q. The range is limited by the minimum distance between the ultrasonic sensor and the water level that can be properly measured, and the (dynamic) equilibrium water level will depend on the section of the slot. A reasonable compromise between resolution and dynamic range can be achieved by a sequence of rectangular slots with increasing widths (with greater width at the top).

For a configuration of three consecutive rectangular slots of widths a_1, a_2 and a_3 and maximum heights above the base of the first slot y_1, y_2 and y_3 (see Fig. 1) the following theoretical relationship can be derived for Q, and the height, h:

$$Q = \tfrac{2}{3}\sqrt{2g}\{a_1c_1[h^{3/2} - (h - y_1)^{3/2}] + a_2c_2[(h - y_1)^{3/2} - (h - y_2)^{3/2}] + a_3c_3(h - y_2)^{3/2}\} \quad (1)$$

where c_1, c_2 and c_3 are the contraction coefficients, assumed to be constant, and the expression accounts for $y_2 < h < y_3$. Typical values for contraction coefficients are around 0.6; thus, Eq. (1) can be used in the stage of the design to find out suitable sets of parameters a_i and y_i for the operation range and resolution. Thus, Fig. 3 shows the corresponding theoretical relationship $Q(h)$ for three different configurations (a_i, and y_i values). In this case, for a target operation range of 0–3 L s^{-1}, the selected widths for the slots were 4, 8 and 12 mm. Details about relative position and lengths of the slots are shown in Fig. 1.

The ultrasonic sensor is powered with 12 V dc. The selected model is designed for an operation range of 5–50 cm. It has a resolution of 0.13 mm and a repeatable accuracy of ±0.1%. The speed of sound (affecting the output of the ultrasonic sensor), v_s, changes with the temperature and a little bit with the humidity, but not with the air pressure. For temperature differences of ±10 °C around an ambient temperature of 20 °C, the resulting changes in v_s are below 0.5%.

The pipe diameter has to be large enough to prevent false echoes from peripheral obstructions or condensed water drops. In this application a PVC pipe with an internal diameter of 153 mm (160 mm external) is used. This size performed well

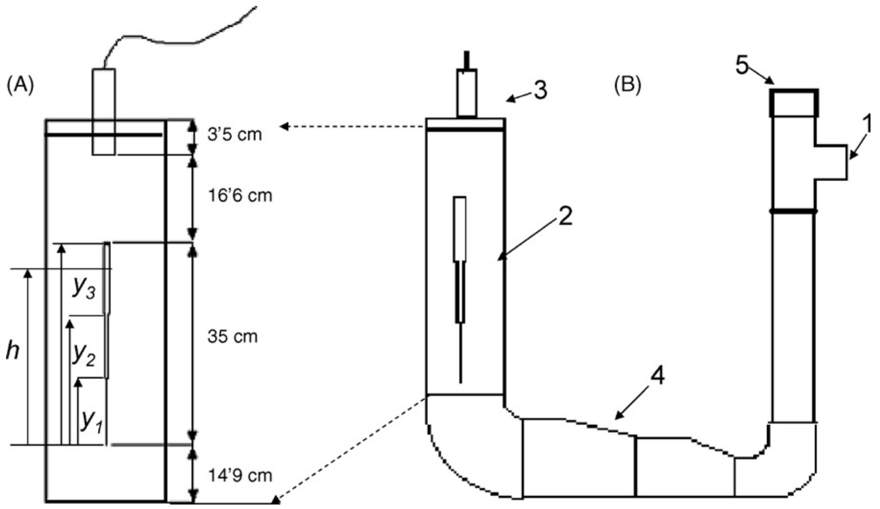

Fig. 1 – Schematic representation of the flow meter. (A) Detail indicating the relevant lengths in the slotted branch. (B) 1, connection to the drain tile outlet; 2, slots; 3, ultrasonic meter; 4, U-connection; 5, removable end cap.

Fig. 2 – Photograph of one of the flow meters operating in field conditions.

in laboratory tests. PVC pipe is used because of its availability, low cost and good mechanical properties.

The ultrasonic meter was connected to a data logger which was also powered with a 12 V battery. The time interval for data acquisition is software selected.

The U shape shows a fast response to changes in input water flows and good water level stability. Measurements will not be affected by suspended loads or air bubbles. Eventual solid deposition at the base of the U-pipe does not affect the measurement of water flows. The instrument requires minimal maintenance. It should be noted that deposited loads could be of potential analytical interest.

2.2. *Calibration*

The flow meter was calibrated in laboratory. Water was pumped from a tank into the flow meter while flow rates were changed and measured using a conventional flow meter for pressured pipes. These flows were correlated with the water levels using the ultrasonic level sensor. Eq. (1) can be used for instrument calibration. Alternatively, second-order polynomial functions were also fit to the calibration data.

2.3. *Field tests*

The experimental site is located in ‘‘Marismas de Lebrija’’ where marsh soils were reclaimed from the estuarine region of the Guadalquivir river, southwest Spain (36°56′N, 6°7′W). A tile

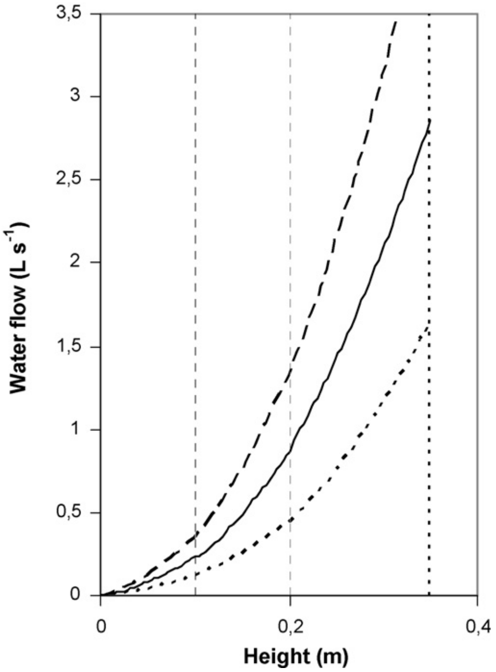

Fig. 3 – Theoretical Q(*h*) relationships (given by Eq. (1)) for three different configurations: 1 (widths 0.2, 0.4 and 0.8 cm, lower dot-line), 2 (widths 0.4, 0.8 and 1.2 cm, central continuous line) and 3 (widths 0.6, 1.2 and 1.8 cm, upper dashed-line). In all the cases y_1, y_2 and y_3 are 10, 20 and 35 cm, respectively, and $c_1 = c_2 = c_3 = 0.62$.

drain system was installed in 1977. After reclamation, these marsh soils were classified as Aeric Endoaquepts (Soil Survey Staff, 1998). More detailed information about the area, reclamation practices and soils can be obtained from Moreno et al. (1981) and Domínguez et al. (2001).

Six rectangular (250 m × 20 m) plots were established. These plots were crossed lengthwise with ceramic drainage lines 250 m long and spaced 5 m apart. These tiles were placed at a depth of 1 m. The two longest sides of the plots (east and west sides) corresponded to drainage lines, which were not included in the study. Drainage flow was monitored in two of the central tile drains of each plot. The south side of all plots was adjacent to a small channel that carried drainage water to the Guadalquivir River. Drain lines had a 0.15% slope towards the channel. The surface of the plots had a 0.1% slope towards the channel to facilitate furrow irrigation and avoid flooding in rainy years. For monitoring purposes, the central drains have been joined. The 6 meters were placed in the central outflow pipes. They were operated from 10 July to late August 2005. A 50 s time interval was selected for data acquisition. The data were downloaded weekly.

3. Results and discussion

Second-order polynomial functions were selected for each slot, because they were easy to use. For the intervals around transitions a cross-calibration was applied. This allowed for the measurements from the ultrasonic sensor be converted by software into water discharges. Table 1 summarizes the calibrated function parameters (a, b, and c) and R^2 (mean and minimum values of 0.9993 and 0.993, respectively) for the 6 meters. Fig. 4 shows a typical calibration curve (for meter no. 2). The flow rate estimated at the mid-range for each slot (q_m in Table 1) varied significantly (the coefficient of variation, CV in Table 1, ranged from 0.15 to 0.17). The CV value could be improved for mass produced devices, but separate calibrations of each meter were required for this work.

The propagated uncertainties in $Q(h)$ at mid-range for the 4, 8 and 12 mm slots are 0.4%, 0.3% and 0.1%, respectively (from the calibration functions—Table 1, and the resolution of the ultrasonic sensor). The instruments performed well in field. Some of the water discharge data are shown in the graph of Fig. 5. They show good signal stability and an important

Table 1 – Calibration of the water flow meters[a]

Slot	Device						CV[b]
	1	2	3	4	5	6	
Width 4 mm, length 10 cm							
a	0.0013	0.0013	0.0013	0.0016	0.0022	0.0013	
b	0.0064	0.0095	0.0102	0.0116	0.0118	0.0095	
c	−0.0176	−0.0189	−0.0250	−0.016	−0.0089	−0.0072	
R^2	0.9991	0.9998	0.9999	0.9997	0.9998	0.9997	
n	6	9	11	10	10	9	
$h'_{min}-h'_{max}$	1.76–12.36	1.52–11.48	1.85–13.12	0.97–10.75	0.47–10.51	0.48–10.69	
h'_{msh}	6.76	6.52	6.85	5.97	5.47	5.48	
q_m	0.085	0.098	0.106	0.110	0.1210	0.084	0.15
Width 8 mm, length 10 cm							
a	0.0015	0.0036	0.0026	0.0027	0.0058	0.0030	
b	0.0115	−0.0369	−0.0216	−0.0032	−0.0700	−0.0253	
c	−0.1091	0.2071	0.1647	0.0177	0.4544	0.1746	
R^2	0.9989	0.9999	1.0000	0.9995	1.0000	1.0000	
n	6	9	8	7	9	8	
$h'_{min}-h'_{max}$	12.56–16.73	11.64–19.71	13.39–23.9	11.1–17.57	10.61–17.55	10.75–18.4	
h'_{msh}	16.76	16.52	16.85	15.97	15.47	15.48	
q_m	0.505	0.580	0.539	0.642	0.753	0.493	0.17
Width 12 mm, length 15 cm							
a	0.0091	0.0014	0.0061	0.0003	0.0035	0.0029	
b	−0.3923	0.0633	−0.2186	0.1281	−0.0122	−0.0325	
c	5.3808	−0.9650	2.8810	−1.7333	0.1366	0.3145	
R^2	0.9933	1.0000	0.9981	0.9999	1.0000	1.0000	
n	5	5	5	5	5	6	
$h'_{min}-h'_{max}$	23.84–36.84	22.14–34.23	24.40–26.78	21.14–34.77	20.50–34.19	20.91–34.22	
h'_{msh}	29.26	29.02	29.35	28.47	27.97	27.98	
q_m	1.69	2.05	1.72	2.16	2.53	1.66	0.17

[a] Fit to a second-order polynomial function $Q(h') = ah'^2 + bh' + c$; with h' (in cm) measured over practical datum levels fixed 0.5–2 cm below the base of the first slot.Slots are defined by their nominal dimensions, n is the number of experimental data points used for calibration, and R is the correlation coefficient. $h'_{min}-h'_{max}$ gives the minimum and maximum value of h' corresponding to the calibration data set for each device and slot. In the first slot (4 mm width), the minimum value of the range always corresponds to the practical datum level, h'_0.
h'_{msh} is the height h' at medium slot height (e.g. $h'_0 + 5$ cm, $h'_0 + 15$ cm and $h'_0 + 27.5$ cm for the first, second and third slot, respectively), and $q_m = Q(h'_{msh})$.

[b] CV = σ_q/q_a. Coefficient of variation; with q_a the mean value of q_m for the six devices, and σ_q the corresponding standard deviation.

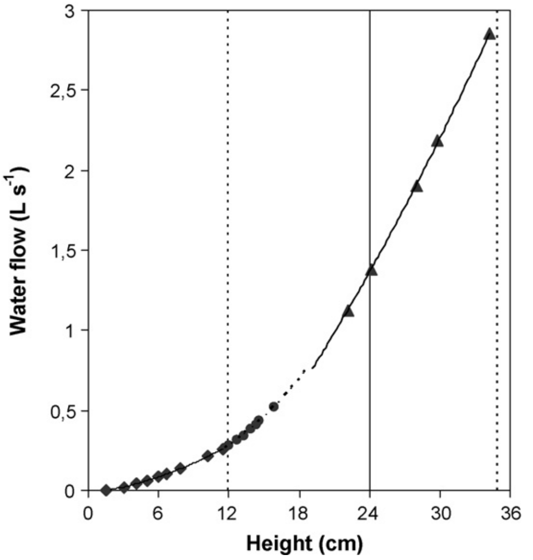

Fig. 4 – Calibration curve for the recording flow meter no. 2. Laboratory measurements (dots) vs. second-order polynomial fit (lines, with fitting parameters given in Table 1) for each slot.

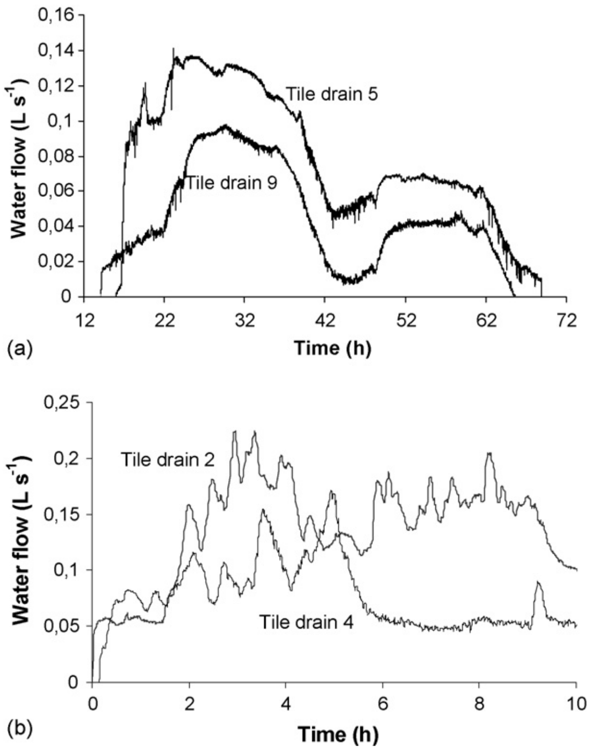

Fig. 5 – (a) Time series of recorded water fluxes in tile drain 5 (upper continuous line) and 9 (dot-line) from the experimental site (time after 0:00 h of 19 August 2005). (b) Detail of the short time scale variability in water fluxes. Time series of recorded water fluxes for tile drain 2 (upper continuous line) and drain 4 (dot-line). Time after 0:00 h of 20 September 2005.

variability that has been accurately resolved with the recording flow meters.

4. Conclusions

The proposed design of a recording flow meter performed well in the laboratory and the field. The ultrasonic water level sensor mounted in a multi-slotted U-pipe demonstrated that it was a suitable design for accurately measuring drain tile discharges. This instrument demonstrated sufficient measurement resolution. The basic design can be adapted for other target ranges. The design used low cost and freely available components.

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