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AN EXPERIMENTAL PLOT FOR HYDROLOGICAL PROCESSES MODELLING

A. Longobardi, P. Villani, V. Foresta and G. Sorbino
Department of Civil Engineering, University of Salerno
Via Ponte Don Melillo, 84084 Fisciano, Salerno
Italy
alongobardi@unisa.it

ABSTRACT
In this paper we describe the data and some preliminary analysis as the investigations of infiltration process, soil water content profiles dynamic and water movement systems, referring to an experimental plot. The broad aim of the work is to test the usefulness for hydrological modelling of a soil moisture monitoring methodology which is based on capacitance devices and has the benefit to be an easy and low cost system. Collected data are expected to be useful to improve the general understanding at the field scale.

KEY WORDS
Modelling, soil moisture, infiltration and runoff coefficient

1. Introduction

The experimental plot, for which an FDR monitoring system has been tested, is located in southern Italy and has an extension of 450 m^2. The FDR technique is similar to the TDR in that the apparent dielectric relationship to soil water content is exploited. Wyman (1930) identified the relationship between capacitance and soil moisture in the late 1920's. However, the use of capacitance based techniques was not possible due to the inability to select oscillating frequencies not influenced by the bulk soil electrical conductivity. Widespread use of frequency-domain (FD) sensors followed development of a down-hole portable instrument (Dean et al., 1987). The data collected consist of soil water content, soil properties, rainfall and air temperature. Meteorological measurements have been collected with an automatic weather station at 10 minutes resolution time. Soil moisture data have been continuously measured at 10 minutes steps, using six capacitance FDR (Frequency Domain Reflectometry) probes. Each probe has four sensors at different depth, thus soil moisture data are available at four levels, 100, 300, 500 and 800 mm. The data collection started in October 2004 and is in progress. So far data for one hydrological year (October 2004 – October 2005) have been analysed. Measured soil water content appears, on average, generally less than 35%, approaching 45% during the main events. Near surface layer seems to be the most responsive to the rainfall input. Deepest soil water content, at 800 mm depth, also appears not to be constant, showing increasing values at the end of rain events. Deep soil moisture response to rainfall is however less evident compared with surface soil moisture one. Soil type and soil heterogeneity play an important role, with soil moisture values being rather different from probe to probe. Dry periods, besides rain periods, have also been investigated in order to analyse the evapotranspiration process. The effect of the relative flux is a negative exponential decreasing soil moisture law.
The data described allow a number of hydrological analysis and can represent a valid support for many hydrological modelling tasks. Measured water stored into the soil during a rainfall event, i.e. the infiltration volume, and storing velocity, i.e. the infiltration velocity, can be used to read and calibrate a number of infiltration models. The proportion of rainfall that is transformed into runoff, the runoff coefficient, can also be estimated from the collected data. During the main events, a large proportion of rainfall has found to not infiltrate the soil surface, producing surface runoff and high runoff coefficient value, which are dependent, as will be later shown, on the wetness conditions.
We believe this monitoring methodology has the potential to be a valuable technique for hydrological processes modeling, both at the hillslope and at the catchment scale.

Fig 1. The experimental site.

2. The Experimental Plot

The plot is located in southern Italy, Campania region, within the University of Salerno's campus. According to a regional analysis and following the Thornthwaite classification the climate is humid, with mean annual rainfall equal to 1170 mm and mean annual potential evapotranspiration equal to 780 mm. Figure 2 shows the entity of rainfall deficit and rainfall excess respectively during the dry and wet season.

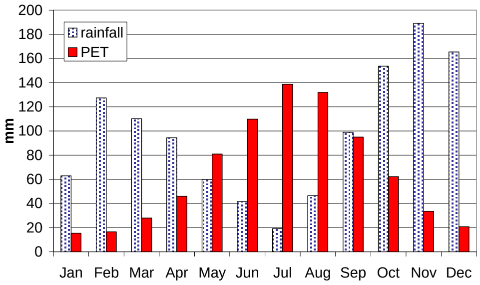


Fig. 2. Mean monthly rainfall and mean monthly PET.

Grain size distribution of collected samples shows a layered soil profile: a first layer ranging from 0 to 200 mm classified as gravel with silt and clay, a second layer ranging from 200 to 600 mm classified as clay with silt sand and a third layer ranging from 600 to 800 mm classified as clayey silt with sand and gravel.
The terrain consist of a smooth 35° slope, with a flat area in the upper part which is contiguous to a car parking. Runoff from the car parking does not flow into the experimental site. The slope is bounded by a 1 m retaining wall at the toe and a wood stairs was realized to cross it. The experimental plot has a 450 m^2 extension (15 x 30 m) and is located 15 m from the parking and 5 m from the stairs, within the slope area. The vegetation consist of perennial lawn grass.
Meteorological and soil moisture measurements started in October 2004 and are in progress. Precipitation and air temperature are measured from an automatic weather station, at 10 minutes time resolution. Six EasyAG (Sentek Pty. Ltd., South Australia) capacitance probes were installed (Figure 3) to continuously measure soil water content at 10 minutes resolution time. The probe consists of an access tube, with a 3.2 cm diameter, where four sensors (2.65 cm diameter) are inserted at 100, 300, 500 and 800 mm below the soil surface. Two data logger are connected to the sensors and to the weather station and data are telemetered back to a remote computer. According to the device design the frequency of oscillation F is related to the capacitance C as in the following expression:

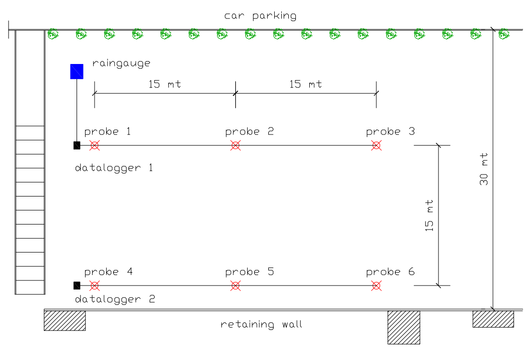
$$F = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

where L is the inductance of the oscillator. To account for the sensor design a scaled frequency SF is derived:

$$SF = \frac{F_A - F_S}{F_A - F_W} \qquad (2)$$

where FA is the frequency in the access tube while suspended in air, FS is the frequency in the access tube in a water bath or a normalisation container and FW is the frequency in the access tube while in the soil at each particular level. Soil electrical capacitance is affected by soil moisture, then the scaled frequency is related to the volumetric soil water content (%), with an exponential relationship.
A laboratory calibration, based on gravimetric water content determination, has been undertaken and is currently in progress to estimates the measurement errors. Measured soil water content are in good agreement with gravimetric laboratory determinations.

Fig. 3. The experimental plot and probes location.



3. Data Analysis

Figure 4 shows the temporal variability of soil moisture over the studied period, over two depth, at probe 1, indicated in Figure 3. The black line indicates the soil water content monitored at 100 mm depth, whereas the green line indicates the soil water content monitored at 800 mm depth. In the same picture the bar chart of daily rainfall is also represented. Both surface soil moisture (100 mm) and deep soil moisture (800 mm) increase at the end of a rainfall event, with surface water content having a rapid increase compared with deep one. The relative increase also depends on rainfall event volume.

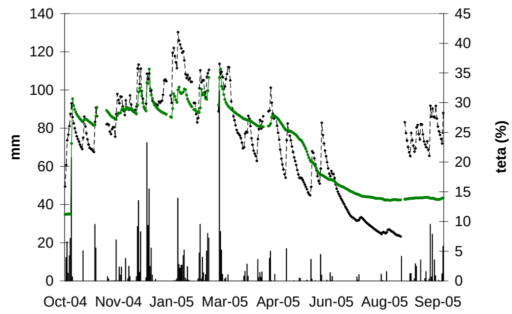


Fig. 4. Temporal variability of soil moisture at probe 1.

During winter time soil moisture approach the highest values (40 % at 100 mm depth and 35 % at 800 mm depth). Because of a very copious rainfall event, almost 100 mm, soil water content is rather high also at the end of winter period.

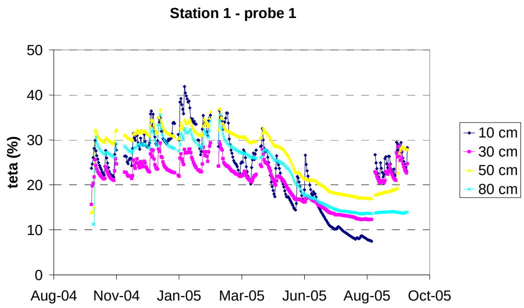


Fig. 5. Temporal variability of soil moisture at probe 1.

Figure 5 also show soil moisture monitored at 300 mm and at 500 mm depth at probe 1. As it can be observed, at each level soil water content dynamic is influenced by rainfall occurrence, with dependence being less evident at deeper depths. Similar temporal patterns have been found at the remaining probes.

Soil heterogeneity is responsible for different behavior at each monitored point. Figure 6 compares soil moisture temporal pattern measured at the six probes, at 300 mm depth.

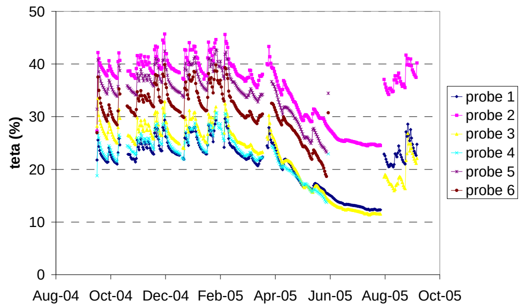


Fig. 6. Temporal variability of soil moisture at 300 mm depth at each monitored point.

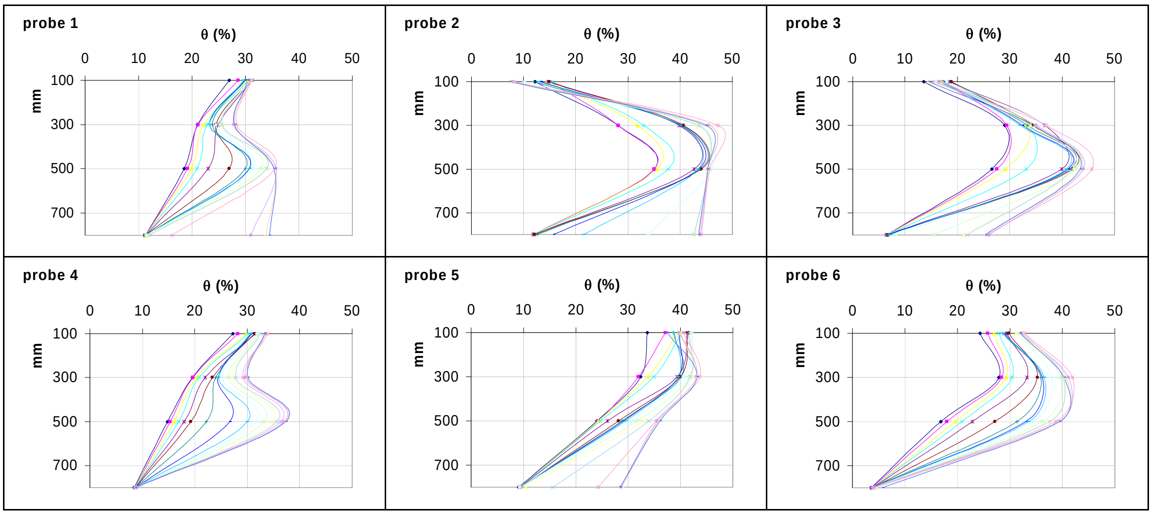


Figure 7. Soil moisture profile for the 26/12/2004 event.

Mean soil moisture values range from a minimum of 22.5% at probe 1 up to 37.3% at probe 2, without any spatial consistence. Same findings hold at 100 mm and at 800 mm depth, while soil moisture monitored at 500 mm appears to be rather uniform over the plot.

Soil moisture profiles have been plotted at each probe for the 26/12/2004 event. The temporal pattern over 15 time steps, of 10 minutes each, is showed (Figure 7). It can be observed the difference in terms of initial soil moisture content and temporal water content dynamic over the time from probe to probe. It can also be noticed the presence of a less permeable layer, ranging between 300 and 500 mm, as it was found during field investigations.

At the end of a rainfall event soil moisture decrease under dry conditions, because of the evapotranspiration flux when no rainfall occurs. Eight dry periods have been selected to investigate this process. Soil water content decrease following a negative exponential law:

$$\theta(t) = \theta_0 e^{-\alpha t} \tag{3}$$

with a mean coefficient of determination r^2 equal to 0.95. Parameters ϑ_0 and α seems to be related to the mean air temperature during the dry periods as illustrated in Figure 8. The coefficient $1/\alpha$ is indicated as it gives an idea of the process delay.

It also appears in Figure 9, where soil moisture values during two dry periods, in winter (blue line) and in spring (red line). Although initial soil moisture values Q_0 are similar, 40.34% in the first case and 38.79% in the second, the parameter α which gives the shape of the function is greater during the spring period, when the air temperature is greater than in winter time and the evapotranspiration flux is then rapid and dominant. The delay time of the drying process ($1/\alpha$) is almost 130 day during the winter event and almost 80 days during the spring event. Besides their values, it is rather evident that the soil acts as a different system in different periods and this behavior would imply a modeling approach which considers the soil as a multiple component output system (Claps et al, 1993).

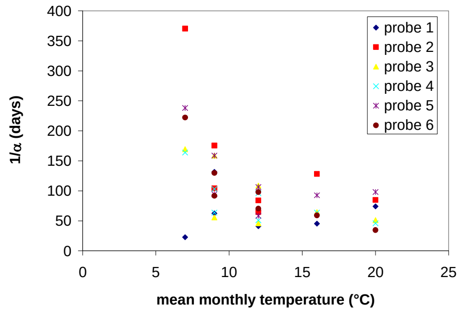


Fig. 8. Mean monthly air temperature versus $1/\alpha$.

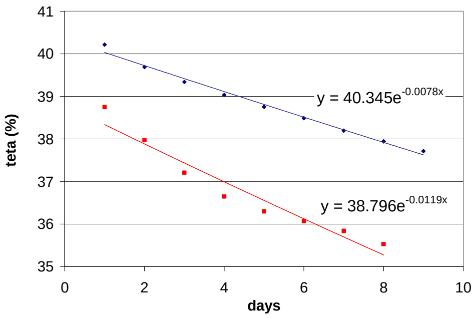


Fig. 9. Daily soil moisture values during winter period (blue line) and during spring period (red line).

4. Hydrological Modelling

The data described in the previous paragraphs allow a number of hydrological analysis.

Rainfall – runoff models simulate infiltration process, among others, with the aim to reproduce effective precipitation to be transformed into runoff. The data presented can be useful to improve the general understanding at the field scale. To show this, an infiltration model is used to read the observed data, i.e. the observed cumulative infiltration volume. Among many (Green and Ampt, 1911; Philip, 1957; SCS, 1972), the Horton model has been chosen because of the reduced number of model parameters to be calibrated and because despite the empirical formulation model parameters refer to soil hydraulic properties. Horton (1933) developed one of the earliest infiltration equation:

$$q(t) = q_c + (q_0 - q_c)e^{-kt} \tag{4}$$

where the infiltration rate q(t) is related to a minimum infiltration capacity qc (mm/h), to an initial infiltration capacity q_0 (mm/h) at t = 0 and to a decay constant k, as he found empirically. The minimum rate qc refers to the same soil characteristics as the hydraulic conductivity, although it is an empirical parameter. The initial infiltration rate can be related to the initial conditions ϑ_i, in terms of soil moisture, as it follows:

$$q_0 = (q_c - q_d)\frac{\theta_i - \theta_d}{\theta_s - \theta_d} + q_d \tag{5}$$

where q_d represent the infiltration rate under dry conditions, corresponding to ϑ_d water content, and ϑ_s is the saturated soil water content. The cumulative infiltration F(t) is evaluated as:

$$F(t) = \int_0^t q(\tau)d\tau = q_c t + (q_0 - q_c)\frac{1 - e^{-kt}}{k} \tag{6}$$

The calibration algorithm estimates the optimum set of (q0, qc and k) minimizing the object function root mean square error (RMSE). A calibration requisite is that $q_0 > q_c$. Figure 10 shows an application to a particular event, where a good agreement exists between the observed and the modelled cumulative infiltration. Estimated model parameters are q0 = 12 mm/h, qc = 0.72 mm/h and k = 8.33 hours, which seem to be consistent with the soil characteristics properties.

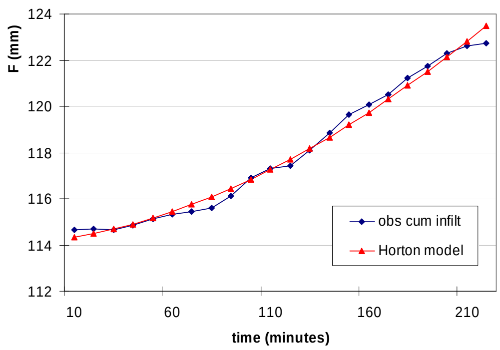


Fig. 10. Observed and modeled cumulative infiltration during 12/10/2004 event.

The relationship between the runoff coefficient, on the event base, and the initial conditions, in terms of soil moisture prior to the event, can also be investigated, with obvious implications in hydrological modeling (Stephenson and Freeze, 1974; Grayson et al., 1995). Fifteen events have been selected from October 2004 to October 2005, on a rainfall threshold equal to 5 mm. The runoff coefficient has been evaluated as the ratio between the runoff volume and the rainfall volume (Table 1). No devices have been installed to measure surface runoff, thus the runoff volume, on the event base, has been estimated from soil water balance between rainfall volume and soil water volume stored, during the event, over 800 mm depth, neglecting the evapotranspiration flux. As it appears in Table 1 there is an adequate consistency in the runoff coefficient values, affected by soil heterogeneity, measure errors and model errors.

As an example, Figure 11 shows the relationship between runoff ratio and soil moisture content prior the event, for the probe 5. It is evident that surface runoff is a threshold process, with the threshold being related to the soil water content. The runoff coefficient is equal to zero until soil water content approaches the threshold value. Soil moisture measured at different depths shows that the threshold value varies between 25 % and 33%, depending on the considered depth.

event	P1	P2	P3	P4	P5	P6
12/10/04	0.00	0.27	0.15	0.00	0.00	0.00
27/10/04	0.00	0.00	0.00	0.20	0.00	0.33
27/11/04	0.98	0.97	0.92	0.23	0.00	0.34
26/12/04	0.48	0.30	0.00	0.48	0.27	0.23
27/12/04	0.59	0.62	0.34	0.59	0.54	0.46
29/12/04	0.51	0.00	0.00	0.51	0.54	0.54
24/01/05	0.10	0.40	0.14	0.34	0.19	0.27
04/03/05	0.49	0.68	0.54	0.58	0.53	0.58
20/03/05	1.04	0.96	0.96	0.97	0.99	1.01
29/05/05	0.37	0.00	0.00	0.13	0.00	0.00
07/06/05	0.00	0.09	0.00	0.00	0.00	0.00
04/09/05	0.00	0.33	0.00	0.01	0.00	0.00
09/09/05	0.00	0.28	0.00	0.45	0.00	0.00
18/09/05	0.00	0.00	0.00	0.32	0.00	0.00
30/09/05	0.00	0.24	0.23	0.35	0.00	0.03

Tab 1. Runoff coefficient evaluated at the six installed probes.

Soil moisture monitoring is in this case, and after all as it is well known in the literature, a key variable to predict runoff volume. Similar conclusions can be drawn from the remaining probes, where the water content threshold varies being affected by soil heterogeneity.

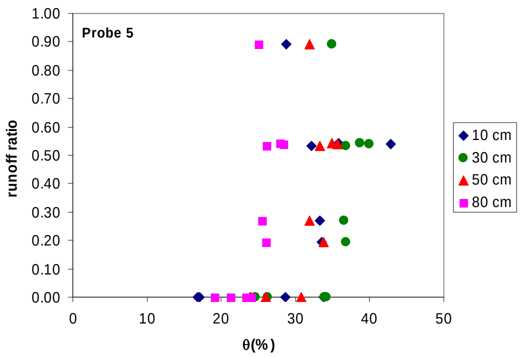


Fig. 11. Runoff coefficient versus initial soil moisture content measured at different soil depth.

Since the runoff volume data are soil water balance estimated, the analysis results may be in part affected by errors induced by the balance. However similar results have been found when the same experiments have been conducted with measured runoff volume data (Longobardi et al., 2003).

5. Conclusion

In this study we have presented data collected from a 450 m^2 experimental plot, located in southern Italy, consisting of soil water content, soil properties, rainfall and air temperature. Meteorological measurements have been collected with an automatic weather station whereas soil moisture data have been continuously measured, at four levels, 100, 300, 500 and 800 mm, using six capacitance FDR. The FDR technique is similar to the TDR in that the apparent dielectric relationship to soil water content is exploited. The data described allow a number of hydrological analysis, as soil water budget estimation, infiltration process investigation and so on. The monitoring methodology seems to be promising for hydrological processes understanding and modelling and some preliminary results have been presented.

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References

[1] J. Wyman, Measurements of the Dielectric Constants of Conducting Media. *Physical Review, 35*,1930, 623-634.

[2] T.J. Dean, J.P. Bell & A.J.B Baty, Soil Moisture Measurement by an Improved Capacitance Technique. Part I. Sensor Design and Performance. *Journal of Hydrology, 93*, (1987), 67- 78.

[3] P. Claps, F. Rossi & C. Vitale, Conceptual- stochastic modelling of seasonal runoff using autoregressive moving average models at different scales of aggregation. *Water Resources Research, 29*(8), 1993, 2545–2559.

[4] W. Green & G. Ampt, Studies on soil physics part I: the flow of air and water through soils. *Journal of Agricultural Science, 4*, 1911, 1–24.

[5] J. Philip, The theory of infiltration: 4. Sorptivity and algebraic infiltration equations. *Soil Science, 84* (3), 1957, 257–264.

[6] Soil Conservation Service-USDA, Estimation of direct runoff from storm rainfall, National Engineering Handbook. Section 4- Hydrology 1972 pp. 10.1–10.24, 1972.

[7] R.E. Horton, The role of infiltration in the hydrologic cycle, *Trans. Am. Geophys. Union, 14*, 1933, 446-460.

[8] G.R. Stephenson & R.A. Freeze, Mathematical simulation of subsurface flow contributions to snowmelt and runoff, Reynolds Ck. Watershed, Idaho. *Water Resources Research, 10*, 1974, 284-294.

[9] R.B. Grayson, G. Bloschl & I.D. Moore, Distributed parameter hydrological modelling using vector elevation data: THALES and TAPES-C. Chapter 19 in, Singh, V.P. (ed.), Computer models of Watershed Hydrology. Water Resources publication, Highlands Ranch, Colorado, pp. 669-696, 1995.

[10] A. Longobardi, P. Villani, RB. Grayson & A.W. Western, On the relationship between runoff coefficient and catchment initial conditions, MODSIM 2003 International Congress on Modelling and Simulation, D.A. Post (ed), Townsville, Australia, 2003, vol. 2, 867-872.