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The use of TDR for wetness measurements in soil erosion and conservation practices in small watersheds

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Introduction

Among all actions regarding water in a watershed, two are especially important within the HYDROMED project for Tunisia. They concern soil erosion and soil conservation, respectively.

The Kamech watershed in the Cap Bon area, represents watersheds with layers of marls and clayey soils, between sandstone. Marl areas supply the most silt to reservoirs. Compared to calcareous soils, it can reach 7 to 1 (Meddi, 1992). In this kind of landscape, linear erosion is more important than interrill erosion. Rills and gullies are an important source of silting and badlands are the ultimate term of soil degradation (Kouri, 1993; GTZ, 1996). In the watershed of Kamech, some creeps appear along the slopes, most of them on the right side of the main drainage net. An important question to answer is what is the effect of water on the erosion along the slopes and especially is there a particular location in the soil where water contributes to creeping and slumping.

The watershed of El Gouazine is situated in the centre of the dorsal mountains. This area is shaped by geological calcareous formations that produced hills and cliffs and by glaciers resulting in silty-clayey deposits covering calcareous crusts. The valleys are are formed from alluvial silts and clays. Mountains and hills are covered with forests and bushes and the slopes are cultivated for cereal cropping and well protected by levelling. These anti-runoff practices have already limited sedimentation and the silting up of the lake. Another important question to answer is what the impact of these anti-runoff practices has on the water circulation. The TDR technique was applied to try to contribute in answering these questions.

Principles of the time domain reflectometry

Theory

Originally the time domain reflectometry (TDR) was used to detect defaults in transmission lines and cables. A voltage pulse is introduced into the cables. The pulse propagates along the cables as an electromagnetic signal in the frequency range of 1 Mhz to 1Ghz. In coaxial lines the electromagnetic field is inside the cable. In parallel lines, the field is both between and around the cables. The pulse shape and the transit time depend on the cable properties, length, and the termination of the cable where the signal is reflected. The TDR equipment typically consists of a 2 or 3 rod transmission line, a coaxial connecting cable, and a TDR instrument to generate fast-increase time pulses and to measure the time. A probe is considered to consist of the transmission line and any structure or component between the transmission line and the connecting cable.

In 1969 Fellner-Feldegg used TDR for measuring the dielectric constant. In 1980, Topp et al. introduced TDR for the measurement of soil moisture. They measured the apparent dielectric constant of a large number of soils and related it to volumetric water content using a third-order polynomial equation (Fundinger et al., 1995):

$$\varepsilon_r = 3.03 + 9.3\theta_v + 146\theta_v^2 - 76.7\theta_v^3$$

Most researchers found this relationship appropriate for their soils, but it is possible to fit a better relationship by a specific calibration. TDR probes with 2 or 3 rods are now also used to measure soil solution electrical conductivity for transient conditions with varying water content. This application allows also non-destructive measurements of solute transport in the unsaturated zone (Persson, 1997; Persson and Berndtsson, 1997).

The TDR technique is based on a measure of the velocity c of an electromagnetic wave in the soil. This velocity depends on the dielectric constant of the soil and the dielectric constant in turn mainly depends on the water content for this specific soil (Fig. 1).

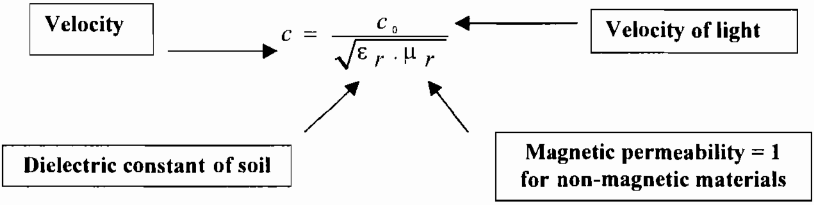


Figure 1. The velocity c must be measured in order to determine the dielectric constant.

Velocity measurement

The wave travels along the 2 or 3 rods of the probe with the length l and is reflected at the end, then returns. Consequently, the velocity c is known by the measurement of the transit time t (Fig. 2).

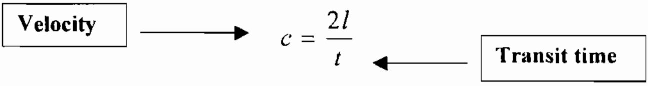


Figure 2. Calculation of velocity by use of the transit time and probe length.

For large-scale measurements, the length of the transmission lines is dependent on the soil type.

In high clay content soils the signal attenuation limits the maximum length to <1m, while longer lines can bee used in sandy soils (Amato and Ritchie, 1995).

The use of short transmission lines for small-scale measurements is limited by the instrument accuracy. For a 15-cm long TDR probe the difference between the transit time in air *ta* and in water *tw* is only 8 ns.

$$t = \frac{2\,l}{c\,o} \cdot \sqrt{\varepsilon\ r}$$

with

$$ta = \frac{0.3m}{3.10^{8}\,ms^{-1}} \cdot \sqrt{1} = 1 \quad ns$$

and

$$tw = \frac{0.3m}{3.10^{8}\,ms^{-1}} \cdot \sqrt{81} = 9 \quad ns$$

Technical realisations

Traditional methods

The reflected TDR pulse is scanned by the sampler. Each point of the pulse signal is measured as a voltage value for a distinct time. The transit time is graphically derived from the voltage signal (Fig. 3). For this expensive high frequency electronic components are needed and the evaluation of the probe transit time part of the curve is difficult for low water contents or short TDR-probe rods.

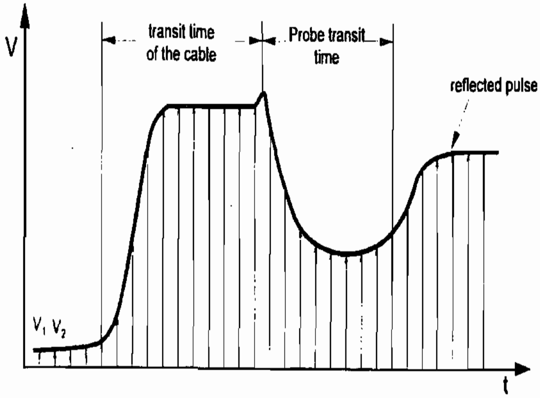


Figure 3. TDR-pulse measurement with the sampling method (from TRIME product guide).

TRIME method (IMKO Gmbh)

Using this method, the points of the TDR pulse are determined by direct time measurements at distinct voltage levels. This requires another pulse shape with a high amplitude of the reflected pulse and a reduction of the attenuation (Fig. 4).

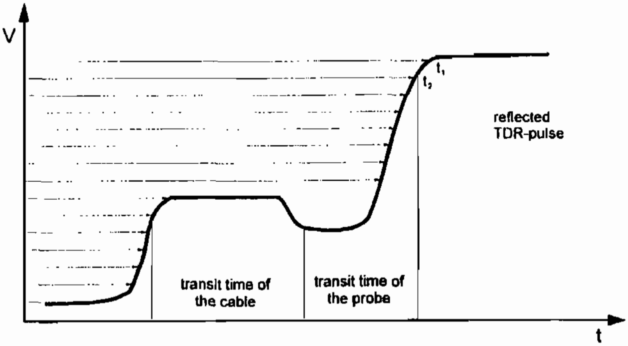


Figure 4. TDR-pulse measurement with the TRIME method (from TRIME product guide).

The shape of the TDR-pulse is formed by a suitable impedance matching the pulse generation output, the connecting cable, and the probe. The coating of the rods with PVC is the second important measure to get this kind of signal:

- low frequencies are blocked
- only high frequencies (>> 300MHz) travel through the soil and can be attenuated.

Thus, the total attenuation is reduced and the amplitude of the reflected pulse is high. A special algorithm derives the amplitude of the reflected pulse from measurements at particular points of the curve. When the amplitude, which depends of the electrical conductivity of the soil, has been determined, the transit time is measured at the corresponding voltage. This gives short measurement times and low power consumption. Because of averaging of many measurements, transit time can be determined with a resolution of 3 ps. This allows one also to work with short rods and with low water contents.

Moisture calculation

Two or three steps are necessary to calibrate the probes according to Fig. 5 and below:

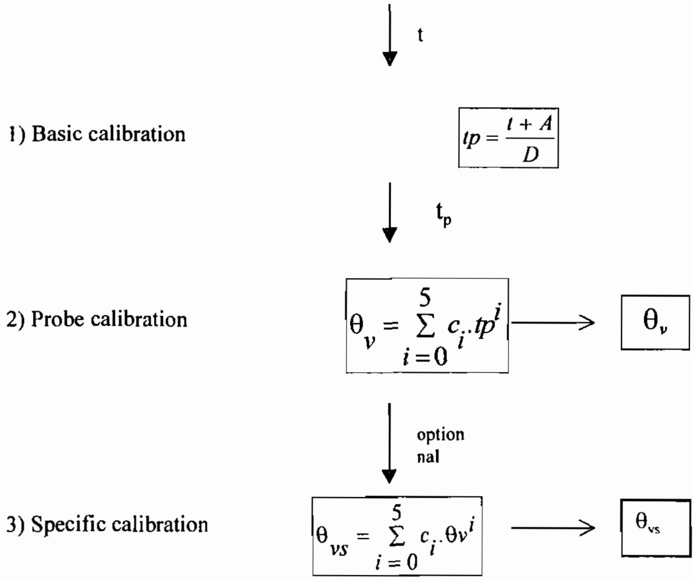


Figure 5. Procedure for the calibration.

1) *Basic calibration*: to compensate cable length, geometry of the rods...each TRIME probe is individually precalibrated,
2) *Standard soil moisture*: calculated for each probe type by a universal calibration function (Topp et al., 1980) for mineral soils.

This calibration procedure is stored in the EEPROM inside the probe connector.

3) *Specific calibration*: the user can calibrate the probe for his specific material.

A measurement table with reference values and TRIME values are designed and used by a calculation program to calculate new C_0 to C_5 coefficients. These new coefficients are stored in the EEPROM.

The TDR station at Kamech

The lake and the watershed

Kamech is situated in the north of the Cap Bon area. The climate here is classified as sub-humid with cool winters (Gounot and Le Houerou, 1968) where annual rainfall can vary from 300 to 1000 mm. The median rainfall is 385 mm (Nabeul, 47 years). The rainfall at Kamech during 1996-97 was 405.5 mm.

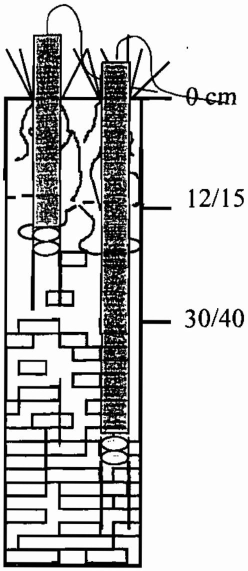
The reservoir at Kamech was built in 1993. The dike is 125 m long and 10 m high. The initial volume of the lake was 142 560 m^3 with a surface at overflow of 4.466 ha. On 31/7/97, silting reached 14 850 m^3 which decreased the initial volume to 127 710 m^3.

The area of the watershed is 245.5 ha with a difference in altitude of 108 m and a slope index of 40 m/km. The morphology of the watershed is formations from Miocene rocks. The watershed is constituted of mainly marl, which was deposited between sandstone banks. The drainage net is formed in the primary area of marl with a main axle parallel to sandstone banks and a secondary network perpendicular to the first. The secondary drainage network is more developed on the right bank and is within secondary valleys with creeps, rills, and gullies. The agriculture for wheat is the main land occupation with range lands for sheep breeding. There is no forest. The water of the lake is used for orchard and industrial tomato irrigation.

The original area, with slopes from 0 to 20%, is planted with annual crops. The secondary valleys, with slopes from 20 to 40%, are range lands.

The soils

The most important area of the watershed is covered with clays and marls. In the upper parts of the valleys, lye calcimagnesic soils with silt and some peaces of an old calcareous crust. The slopes of the valleys are eroded clay soils on geological marls such as the one described below. These soils are swelling clays so that, in the dry season, they produce very large and deep cracks. At the bottom of the slopes, we find alluvium with also swelling clays and some hydromorphic characteristics with depth.



Surface horizon, wet, clayey, plenty of roots.

Transitional horizon, with fine marl pieces (1 to 3 mm) included in the silty clay matrix, some roots.

Beginning of geological marls, having more numerous pieces of marl from 3 to 10 mm, very few roots.

Figure 6. Soil profile along the sloping side and TDR location.

The creeping occurs between the second and the third horizon, generally at the beginning of the geological layer (Fig. 6). In winter, it is believed that differences in soil moisture capacity between the two main layers can contribute to creeping and slumping. In summer, cracks up to 5 cm wide at surface can reach more than one meter depth.

The TDR station

Location of the TDR station

The site is located on the slope of a secondary valley, on the right side of the main river, next to the reservoir. The downstream area of this valley displayes a creep line at the third bottom of the slope. The slope is 34 m long and the TDR are installed at 12, 14, and 16 m from the ridge. Totally 6 TDR probes have been placed along the valley side, upstream the creep. They are arranged in three groups, each group includes 2 probes, one between 15-30 cm and the over between 50-65 cm depth (Fig. 6). The central group is close to a slope change, the upper one, is 2 m upstream and the lower one is 2 m downstream. This is due to the limited length of the cables.

Equipment of the TDR station

The probes

We have chosen P2Z type probes with a large distance between the rods because they can be fitted into the clayey soil with 20-30 mm peds (Fig. 7).

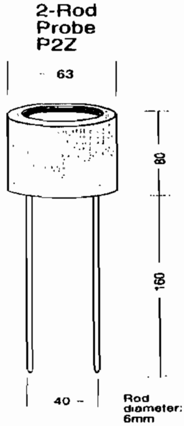


Figure 7. Design of a P2Z probe.

The multiplexer

The six probes are connected to a TRIME MUX 6 for multiplexing (Fig. 8). The probes must be connected to individual plugs because of the individual calibration. In operating mode the measurement control (sample rate, start time etc...) is started by a software installed in the datalogger.

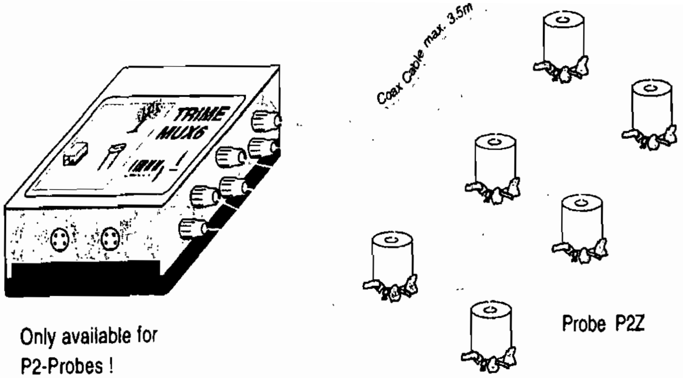


Figure 8. Design of the TRIME MUX6.

The datalogger

The datalogger is connected to the TRIME MUX6 with an IMP 232 micronet wire (Fig. 9). The datalogger is within a waterproof rugged aluminium case including a HP laptop-PC with a PCMCIA Sram chip-card and a software (INMEWA) for the management of the measuring circuit and storage of the data. The complete system is powered by a 12V battery.

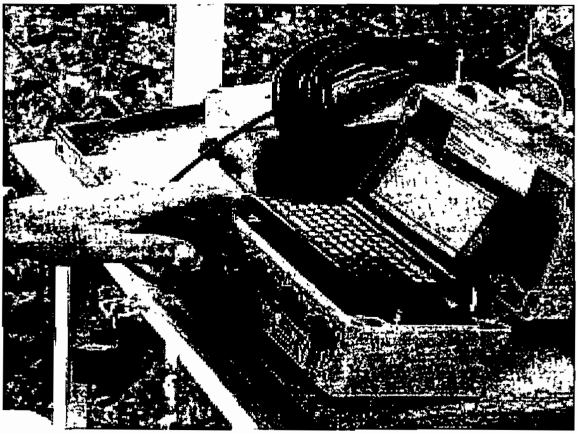


Figure 9. The datalogger.

Technical data

Power-supply: 7-15V DC
Supply current: 8 mA standby, 350 mA while 10-15 seconds measuring time per channel.
Measurement range: 0-70% volumetric water content
Conductivity range: 0-6 mS/cm for P2, P2Z, P2G probes
Accuracy: depends on the calibration for the soil type. Standard calibration for P2Z probes:
moisture range 0-40%: +-1%,
moisture range 40-70%: +-2%.
Repeated accuracy: +-0.3%.
Temperature range: -10 to 45°C

Preliminary results

All the soil moisture data are given according to standard calibration of the probes. Measurements began on 18 of February 1998, each day, at 0h 6h 12h and 18h. We have selected the 12h data to illustrate our purpose, we will later look at the variability between the hours.

The data will be analysed first for each group of 2 TDR probes, according to depth and in a second time, for each depth along the slope. Rainfalls are also on the graphics to illustrate the response of the soil.

Soil moisture according with depth

Figure 10 shows soil moisture according to depth for the upper observation group (AM). Until 10 of May, the bulk soil moisture mainly remained between 30 to 35%. But there was a large variation for the entire period, 18 to 40%. There was a significant response to rainfall for the two soil layers. From 18/2 to 30/3 there was a dry period. The moisture decreased for the first layer and increased for the second layer. It is probable that evaporative forces acted on the first layer and water transfer, not necessarily from the upper layer, but more certainly by lateral flow appeared along the slope for the second layer.

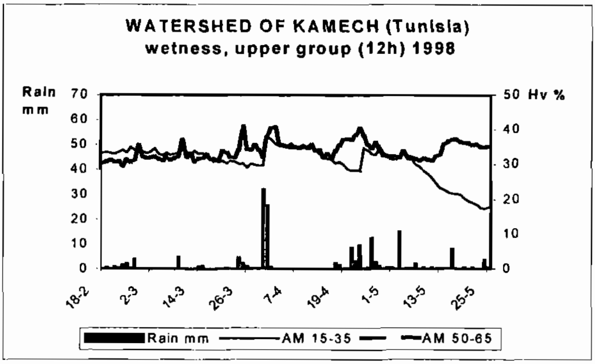


Figure 10. Watershed of Kamech, soil moisture variation, upper site.

From 25/4 to 25/5, two periods can be distinguished: a first one, with a length of about 15 days, where there was a decrease of moisture for the two layers because of efficient capillarity links. During the second one, there is a disrupture of the capillarity links because of an increase in cracks and the soil matrix divides into smaller aggregates that act as mulch. The first layer becomes increasingly dry because of no supply of water from the bottom layer. The moisture of the second layer can increase because rainfall bypasses the first layer directly into the cracks.

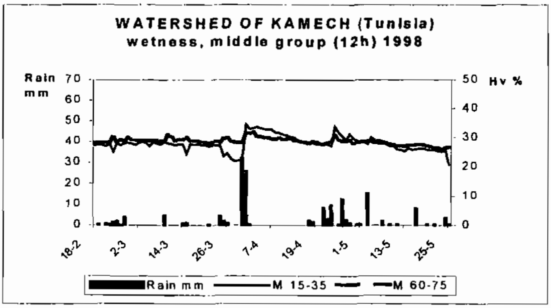


Figure 11. Watershed of Kamech, soil moisture variation, central site.

Figure 11 shows soil moisture with depth for the central observation group (M). The moisture is lower than for the upper observation group, most of data are between 25-28%. There is also a significant response to the main rainfall during the period, particularly for the first layer. During the measurement period, the variation remains small (25-35%) with a slow decrease for the two layers at the end of the rainy season. Here the capillarity links remain for a longer time than at the upper location. These links appear to stop functioning around 25/5.

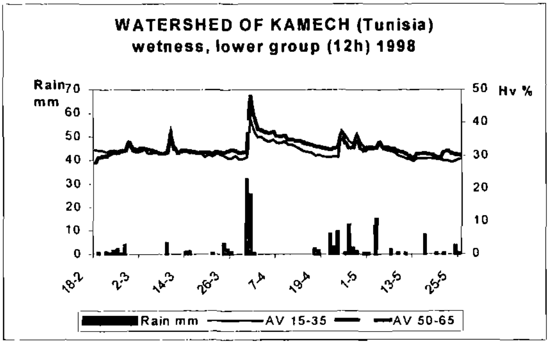


Figure 12. Watershed of Kamech, soil moisture variation, lower site.

Figure 12 shows the soil moisture with depth for the lower group (AV). Compared to the upper group there is a quite constant moisture level during the measurement period. As for the central site, moisture does not decrease very much at the end of the rainy season. Soil water remains around 30% but there is a significant response to the main rainfall for the two layers and particularly for the second layer. Average soil moisture is greater than for the central station. Capillarity links remain functioning until 25/5.

Soil moisture variation along the slope

Figure 13 shows soil moisture variation along the slope for the upper soil layer. During the entire rainy season, the upstream site is wetter than the downstream but here the soil moisture decreases faster after the rains. The central site is the driest (1). The central site remains the driest until start of the dry season (2). At the beginning of the dry season, soil moisture increases along the slope from the upper to the lower site because the upstream site dries faster (3).

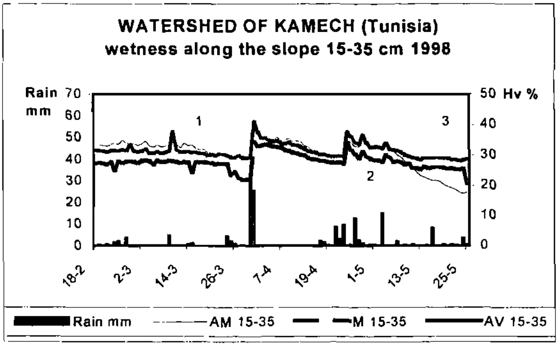


Figure 13. Watershed of Kamech, soil moisture variation along the slope.

Figure 14 shows the soil moisture variation along the slope for the bottom layer. In the first part of the measurements, there was no significant difference between upstream and downstream locations (1). The central site was also the most dry but for these depths it remained the dryer even in May and its response to rainfall was small.

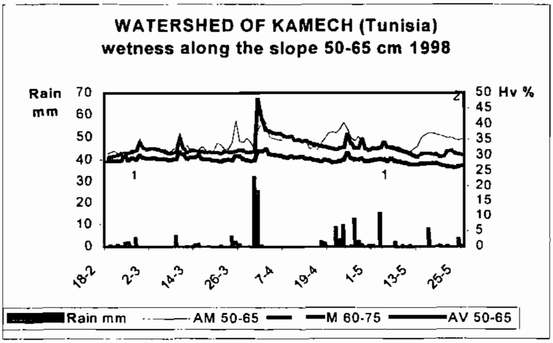


Figure 14. Watershed of Kamech, soil moisture variation along the slope for the bottom layer.

In the beginning of the dry season (2), soil moisture slowly decreased for the central and the downstream site while the upper site firstly displayed an increase. This is difficult to explain except by lateral flow from the upper part of the hillside. For bottom layers, at the beginning of the dry season, the upper site was the wettest.

These results confirmed the behaviour shown in Figs. 10 and 11. There are two drying processes. For upslope areas, an early break of the capillarity link between the upper and lower soil layers and for downslope areas the supply rate of water from the bottom to the upper soil layer.

Variability of data

To increase the information and effects on rainfall variation, measurements were taken four times a day, at 0, 6, 12, and 18 h.

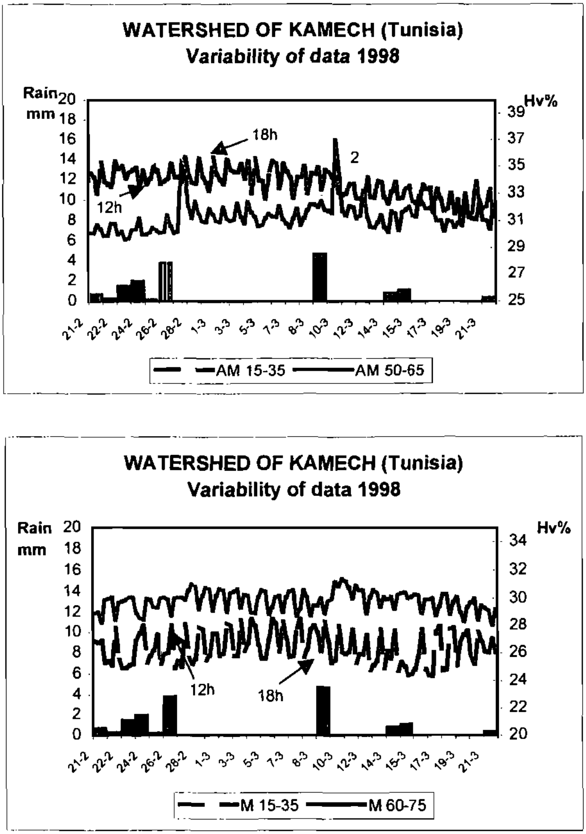


Figure 15 and 16. Watershed of Kamech, variability of data for the central site.

For an example, data variability was investigated for the period from 21/02 to 21/03, with several rainfalls. Figures 15-17 show the four measurements per day during this period. It appears that there is a daily cycle and perhaps some erroneous measurements.

Points 1 and 2 in Fig. 15 can be considered as errors, because the rainfall is too small to give rise to such an increase in soil moisture between 15 and 35 cm depth. However, the same phenomenon is seen for the downstream site (Fig. 17). The reason was a general disturbance of the measuring circuit.

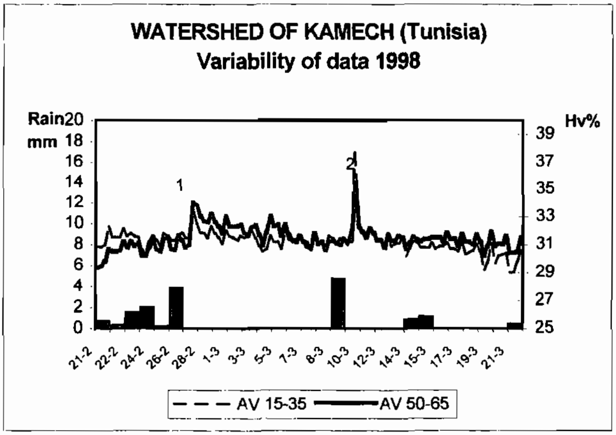


Figure 17. Watershed of Kamech, variability of data for the lower site.

If we compare Figs. 15-17, we notice a significant daily cycle in soil moisture for two to four observations per day. Temperature dependence can be the reason for this but for the upstream site (Fig. 15) most of the elevated values were observed at 18 h and the lower values at 12 h while for the downstream site, these observations were reversed.

Individual calibration

Figure 18 shows the outcome of the first trial to obtain individual calibration curves. Standard calibration is certainly sufficient for most soils. However, in the case of swelling soils, we suspected that absolute values of soil moisture would be different between TDR and gravimetric (105°C) samples. Between February and May samples of soil were taken with an auger at 0.5 m distance from the TDR probes and at the same depth. One hole per site was sampled. These preliminary results showed that it is not possible to get good individual calibration curves except perhaps for the S1 and S2 probes.

Table 1. Bulk soil densities.

BULK DENSITIES (251,32 cm3 cylinders)

date		5-10 cm	15-20 cm	35-40 cm
13/02/98		1,36	1,43	1,45
		1,38	1,38	1,52
27/03/98		1,48	1,36	1,45
		1,42	1,3	1,4
average		1,41	1,37	1,46
standard dev		0,053	0,054	0,049

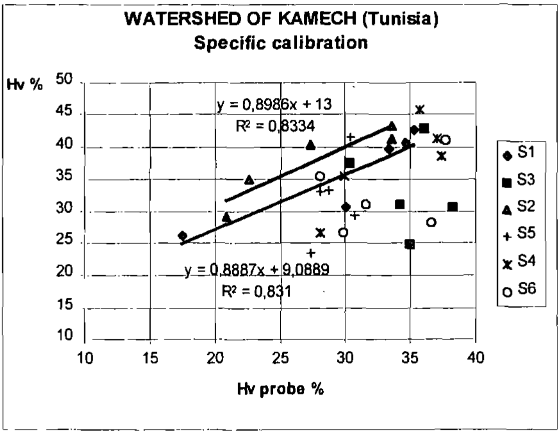


Figure 18. Watershed of Kamech, individual calibration.

A small range in soil moisture variation and the presence of swelling clays may explain these results. In swelling clay soils, moisture can vary greatly for short distances and bulk density changes with soil moisture. This is shown in Table 1. Samples taken at 13/2 are representing a dry period and samples taken at 27/3 are representing a wet situation (just after a rainfall). There was no effect on the 35-40 cm bulk density but a big change for the 5-10 cm bulk density. The rainfall increased the bulk density where there were no cracks. Samples need to be taken to obtain shrinkage curves and a laboratory calibration based on undisturbed soil is needed.

The TDR station at El Gouazine

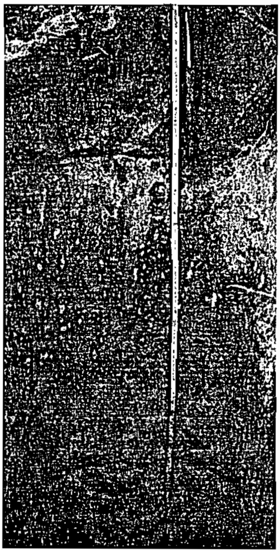
The reservoir and the watershed

El Gouazine is situated in the centre of the Tunisian Dorsal mountains, at 50 km northeast of Kairouan. The climate is semiarid with cool winters (Gounot and Le Houerou, 1967). Annual rainfall is very erratic and varies from 200 to 800 mm with a median rainfall of 358 mm (Ousseltia, 47 years). The rainfall during 1996-97 at El Gouazine was 252.5 mm.

The reservoir of El Gouazine was built in 1990. The dike is 232 m and 10.6 m high. The initial volume of the lake was 233 370 m^3 with a surface at overflow of 9 597 ha. On 10/06/97, silting reached 16 030 m^3 and the reservoir thus had an effective volume of 217 340 m^3.

The area of the watershed is large, 1 694 ha, but the difference in altitude is not important, 199 m, for a slope index of 18 m/km. The watershed is long (11.3 km) and narrow (1.6 km). Most of the soils are developed on quaternary deposits (silt and clay), often with calcareous crust. The elevated parts are on geological calcareous outcrops from the end of the cretaceous era (Campanien and Maestrichien).

Soil occupation is divided between forest (35%) and agriculture (55%). Forest with pine trees and xerophytic shrubs occupies the hilly parts. Annual crops (wheat and fallow) grow on lower parts with some olive trees. Pasture areas are on calcareous crusts. Nearly all the cultivated areas are protected by large soil terracing. Figure 19 shows a typical soil profile of the area.



0-30 cm: plowing layer to 12 cm, fresh to wet, brown, silty clay, fine subangular blocky structure, many fine roots, some calcareous pseudo-mycelium and soft nodules from 12 to 30, fine and medium pores.

30-95 cm: dry, yellowish brown, silty clay, angular blocky structure when wet, massive when dry, some calcareous nodules, hard consistence, no roots.

>95 cm : fresh to wet, yellowish brown, sandy clay loam, firm to friable consistence, fine pores.

Figure 19. Soil structure and texture with depth.

The TDR station

The observation site is established on a slope (6 to 11%), protected by large new soil terraces. Soil occupation is production of cereals and fallow.

Two kinds of data are collected:

- spatial soil moisture with a surface probe, in the area between two soil terraces, and
- linear variations along the slope with three groups of 2 probes. One group is upstream a soil terrace (U1), the two others downstream (D1 and D2) a soil terrace.

Table 2. El Gouazine, position of the TDR probes.

U1		D1		D2	
P1	P2	P3	P4	P5	P6
45-60 cm	75-90 cm	45-60 cm	80-95 cm	30-45 cm	80-95 cm

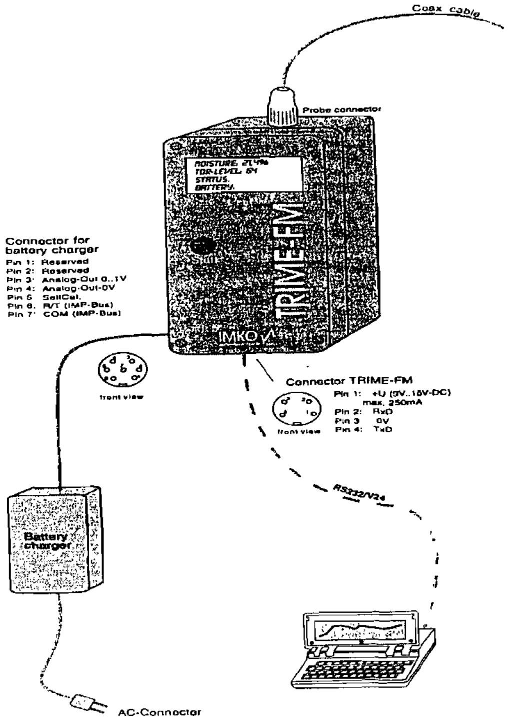


Figure 20. The hand measurement device: TRIME-FM.

For this kind of study on a large area and in ploughed fields it is impossible to use a datalogger with a network of connected cables. The TRIME-FM (Fig. 20) is a portable instrument developed for mobile field use. The four lines of the LC-display are used for soil moisture (%), TDR level, status and error messages, and battery level. The TRIME-FM for 3-rod probes does not accept 2-rod probes. Three kinds of probes are used: one for surface measurements, one for upper layer of the soil (0-15 cm) (Fig. 21), and one for deeper measurements (P3Z probes, Fig. 22).

The probe for surface measurements is only available with 3 rods. This means that if the surface probe is needed, all the other probes must be of 3 rod type unless two TRIME-FM are used. The device has no inner memory but datalogging is possible with a portable computer.

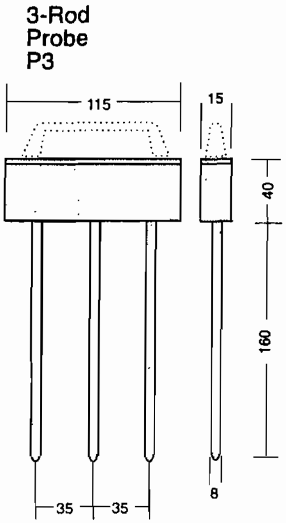


Figure 21. Surface layer probe.

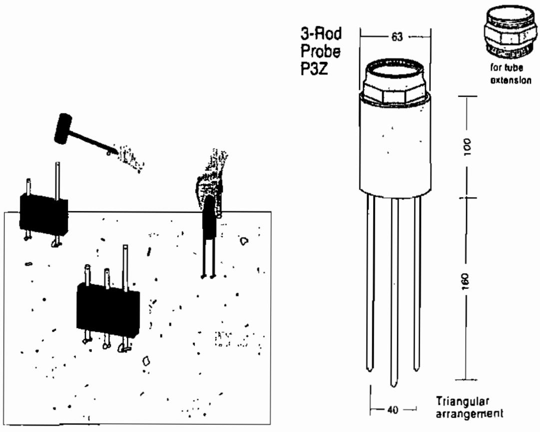


Figure 22. Surface and bottom layer probe.

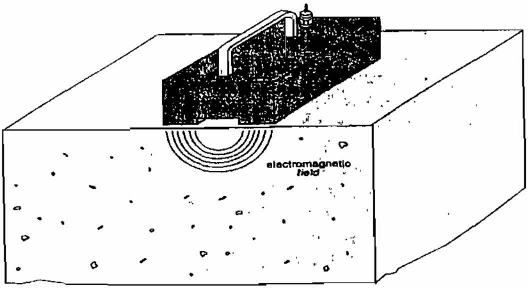


Figure 23. The probe for surface measurements (3 rods; from the IMKO manual).

Preliminary results

Variability along the slope

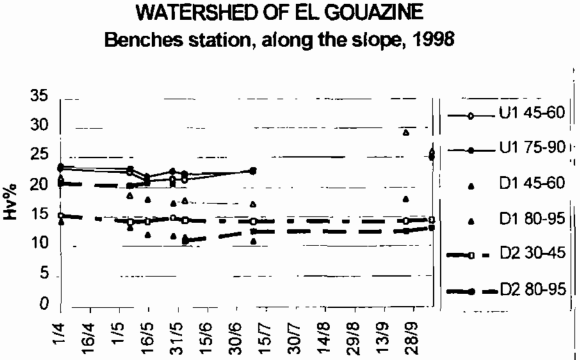


Figure 24. Watershed of El Gouazine, soil moisture variations.

The results showed that variations of soil moisture were very small during the observation period. However, only a few measurements are still at hand. This is because of the manual procedure and complicated measurements. Consequently, it is difficult to have measurements just before and after rainfall to obtain the response of the soil. In any case, there were a few rainfalls during the period. The most important rainfalls were: 13.1 mm on 25/1, 10 mm on 26/2, 16.2 mm on 30/3, and 8.3 mm on 27/4.

The observations also showed that the upslope site is the wettest and that soil moisture is almost constant with depth. At the D1 position, next to the downslope part of the soil terrace, the upper soil layer is always wetter than the deeper one. This may be an effect of the terracing.

For the D2 position, data are possibly erroneous (level 10) because of not parallel rods. This was restored on 3/6/98.

Spatial variability

This kind of measurements was coupled with the use of a Leica "laser tacheometer TC 805" to have the spatial position of each point of the TDR measurement in the field. The TDR data were obtained by the TRIME-FM connected to the surface probe. This use of the TDR probe was very efficient for a quick control of spatial soil moisture variation. Figure 25 shows an example of this for an area between two soil terraces, one part is a fallow area and the other one has been ploughed.

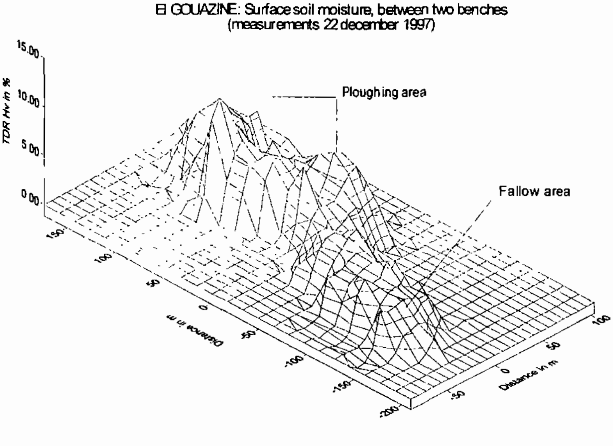


Figure 25. Surface soil moisture variation between two soil terraces.

Conclusion

Two main conclusions can be made regarding the above preliminary results on the use of TDR for soil moisture measurements for soil erosion and conservation practices in small watersheds. One concerns the results and the other the equipment. The results showed that:

- There are heterogeneity effects on the soil water transport in the hilly landscape of Kamech. This heterogeneity works along the slope and between the two soil layers. A first explanation of the dynamics of soil water along the slope can be done. Firstly, structural changes, due to the type of clay, create cracks which are connected. This creates an underground network for water flow and a drainage from upslope to downslope, so that the downslope part is wetter and even may retain more rain water as compared to the upper part. The observed wetness shows that the capillary pump can act from the bottom to the upper part of soil layers for downslope areas. On the other hand, for upslope areas, there is a lack of water, the upper soil layers become dry and the capillarity links with the bottom layer are interrupted.

- It should be possible to show the spatial effects of soil terracing on water infiltration. However, it needs a good coordination between rainfall occurrence and the manual data observations.

Regarding the TDR equipments:

- They permit to follow changes in soil moisture in the two instrumented watersheds.
- The different observation systems fit well together.

However,

- The datalogger needs probes with coaxial connecting cables: it is impossible to use such a network on large areas in the field (because of cattle, cultural practices, etc). An independent TDR system with a small memory card for each probe and an electrical supply by solar cell panels and battery for two or three probes will allow to assess soil moisture at different depths for each location.

- The TRIME-FM permits, on the other hand, installment of probes on large areas, but has no internal memory and high frequency measurements require long time.

- The individual calibration of the probes seems not so easy, particularly in swelling soils. This is mainly due to the heterogeneity on soil water transport (Yasuda et al., 1996a; 1996b). A specific laboratory calibration experiment seems necessary for these particular soils.

References

Amato, M., and Ritchie, J.T., (1995) Small spatial scale soil water content measurements with Time-Domain-Reflectometry. Soil Sci. Soc. Am. J., 59, 325-329.

Fellner-Feldegg, J., (1969) The measurement of dielectrics in the time domain. J. Phys. Chem., 73, 616-623.

Fundinger, R., Köhler, K., and Stacheder, M., (1995) Measurements of material and soil moisture with the TRIME-method. TRIME Product Guide, IMKO GmbH, Ettlingen, 22 p.

Gounot, M., and Le Houerou, H.N., (1968) Carte bioclimatologique de la Tunisie septentrionale. In Climatologie et bioclimatologie de la Tunisie septentrionale, annales de l'institut National de la Recherche Agronomique de Tunisie, vol. 41, fasc. 1.

GTZ, (1996) L'aménagement des zones marneuses dans les bassins versants des montagnes de l'Atlas Tellien semi-aride. Schriftenreihe der GTZ n°256, 142 p.

Kouri, L., (1993) L'érosion hydrique des sols dans le bassin-versant de l'oued mina. Etude des processus et types fonctionnels de ravins dans la zone des marnes tertiaires. Thèse doctorat Univ. Louis Pasteur, Strasbourg, mention géographie physique, 238 p.

Meddi, (1992) Hydropluviométrie et transport solide dans le bassin versant de l'oued Mina. Thèse de doctorat Univ. Louis Pasteur, Strasbourg, mention géographie physique, hydrologie de surface, 103 p.

Menachem, A., (1996) Soil erosion, conservation and réhabilitation. Soil Erosion Research Station, Soil Conservation and Drainage Division, Ministry of Agriculture, Emek-Hefer, Israel. Marcel Dekker Inc, New-York, Basel, Hong-Kong. 402 p.

Persson, M., (1997) Non-destructive measurements of solute transport in the unsaturated zone using Time Domain Reflectometry, Report 3212, Department of Water Resouces Engineering, Lund Institut of Technology, Lund University, Sweden. 41 p. 3 appended papers.

Persson, M., and Berndtsson, R., (1997) Soil texture and Electrical Conductivity Effects on temperature dependance of TDR Measurements, in Report 3212 appended paper 3. Department of Water Resouces Engineering, Lund Institut of Technology, Lund University, Sweden. 41 p.

Topp, G.C., Davis, J.L., and Annam, A.P., (1980) Electromagnetic determination of soil water content : Measurements in coaxial transmission lines, Water Resour. Res. 16, 574-582.

Yasuda, H., Berndtsson, R., Persson, H., Bahri, A., and Jinno, K., (1996a) Tracer experiment in a semiarid clay soil. Department of Water Resources Engineering, Lund Institut of Technology, Lund University, Sweden. Report n°1016, p. III-1 to III-16.

Yasuda, H., Berndtsson, R., Persson, H., Bahri, A., and Takuma, K., (1996b) Characterizing preferential transport in a semiarid heavy clay soil using dye. Department of Water Resources Engineering, Lund Institute of Technology, Lund University, Sweden. Report n°1016, p. VI-1-1 to VI-11.

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