# MODELING DISTRIBUTIONS OF WATER AND DIELECTRIC CONSTANTS AROUND LANDMINES IN HOMOGENEOUS SOILS

Jan M.H. Hendrickx, Bhabani S. Das, and Brian Borchers
New Mexico Tech, Socorro NM 87801
hendrick@nmt.edu

## ABSTRACT

Many sensors for landmine detection are affected by soil water content, temperature, electrical conductivity and dielectric constant. The most important of these is water content since it directly influences the three other properties. We model water distributions around antitank mines buried in a loam and loamy sand soil under the climatic conditions of Bosnia and Kuwait. In Kuwait the loam and loamy sand have mean soil water contents of about 16 and 7 volume percent, respectively; in Bosnia, the mean water contents are higher with means of 30 and 14 volume percent in the loam and loamy sand. As a result the soil dielectric constant in Kuwait varied from about 4 to 8 in the loamy sand and from 8 to 14 in the loam. In Bosnia the higher water contents resulted in a soil dielectric constant from 4 to 12 in the loamy sand and from 9 to 50 in the loam. Water contents below the landmine were sometimes higher than above it. The modeling results demonstrate that soil water content regimes and the resulting distributions of soil dielectric constants around landmines are strongly affected by the interaction between climate, soil type, and landmine geometry.

**Keywords:** soil water, dielectric constant, modeling, Kuwait, Bosnia, soil type, climate, antitank mine.

## 1. INTRODUCTION

The detection and disposal of anti-personnel and anti-tank landmines is one of the most difficult and uncontrollable problems faced in ground conflict. Since mines remain lethal long after military actions have terminated, they also have become a humanitarian disaster. Today at least 100 million landmines are scattered across more than 60 countries.

Presently, a wide range of new sensors has been developed or is in development for the detection of buried non-metallic and low-metallic landmines. Although several of the new sensors are performing quite well under certain conditions, there is general agreement that none of the present technologies is capable of reaching, in a very large number of situations, good enough detection while maintaining a low false alarm rate.[1] One reason is the variety of landmines: there are some 2,500 mine and “fuse” combinations.[2] Another important reason is that the environments in which mines have been placed are extremely variable. For example, the three countries that have the largest average number of mines deployed per square mile are Bosnia-Herzegovina in a temperate zone, Cambodia in the humid tropics, and Egypt in an arid desert.[3] One critical environmental variable is soil water content since it directly influences the thermal and electrical soil properties that interfere with many mine sensors.[4,5,6,7]

The water content of a soil depends on a large number of variables such as precipitation, evapotranspiration, soil, vegetation, depth to ground water table, and topography. The physical principles driving the soil water regime are well understood[8,9] and the modeling of soil water regimes for agricultural or environmental purposes is becoming a standard practice.[10] In addition, several mathematical and experimental studies have investigated water movement around stones or air-filled cavities in the soil.[11,12,13,14,15,16,17] Since the obstructions to water flow caused by stones and cavities are similar to those caused by landmines, the results of these studies indicate that existing soil water flow models are appropriate to model water distributions around landmines. The objective of this paper is to model temporal and spatial changes in the distributions of water and soil dielectric constant around landmines.

## 2. THEORY

### 2.1. Physics of Water Flow in Soils

The principles of water flow in soils is presented in many text books at an introductory[9,18,19,20,21] and advanced level.[22,23,24]

Water movement in the unsaturated zone occurs as a result of gradients in the total hydraulic head $H$:

$$H = h + z \tag{1}$$

where $h$ is the matrix head (m) and $z$ the elevation head or height above a reference level (m). According to Darcy's law, water movement through a one-dimensional, unsaturated, vertical soil column is mathematically expressed as:

$$q = -K(h)\frac{dH}{dz} = -K(h)\frac{dh}{dz} - K(h) \tag{2}$$

where $q$ is the water flux (m/s) and $K(h)$ the unsaturated hydraulic conductivity (m/s). Under transient conditions, when water content changes with time, conservation of matter is accounted for by the continuity equation:

$$\frac{\partial\theta}{\partial t} = -\frac{\partial q}{\partial z} - R_w \tag{3}$$

where $\theta$ is the volumetric water content ($m^3/m^3$), $t$ is time (s), and $R_w$ the root water extraction ($m^3/m^3/s$).

Combining equations (2) and (3) yields

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z} K(h)\left[\frac{\partial h}{\partial z} + 1\right] - R_w \tag{4}$$

Expanding $\delta\theta/\delta t$ by the chain rule as

$$\frac{\partial\theta}{\partial t} = \frac{d\theta}{dh}\frac{\partial h}{\partial t} = C(h)\ \frac{\partial h}{\partial t} \tag{5}$$

where $C(h)=d\theta(h)/dh$ is the soil water capacity, being the slope of the soil water retention curve $\theta(h)$, yields the unsaturated flow equation:

$$C(h)\ \frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\ K(h)\ \left[\frac{\partial h}{\partial z} + 1\right] - R_w \tag{6}$$

To solve this equation two hydraulic soil properties are required: the water retention curve $\theta(h)$ and the unsaturated hydraulic conductivity curve $K(h)$.

### 2.2. Hydraulic Soil Properties

Hydrualic soil properties can be obtained by field or laboratory measurements or by indirect methods.[25,26,27,28] The latter ones use statistical relationships for the prediction of hydraulic soil properties from easily measured data such as texture, particle size distribution, bulk density, organic matter content, water content and water tension measurements. These methods can generally be used with existing field data obtained from soil maps. Their application is therefore more convenient and far less costly then direct measurements. A general consensus exists at present among vadose zone hydrologists and soil physicists that these indirect methods often yield estimates of water retention and unsaturated hydraulic conductivity curves with an accuracy that is quite acceptable for many applications.[27] Indirect methods will be the method of choice for hydraulic soil characterization in mine fields.

One frequently used indirect method is based on the Van Genuchten parameters.[29] He proposed the following continuous functions for the soil water retention and unsaturated hydraulic curves:

$$\frac{\theta-\theta_r}{\theta_s-\theta_r} = [1/1+(\alpha h)^n]^m \quad \textbf{(7)}$$

$$K(\theta) = K_s \left[\frac{\theta-\theta_r}{\theta_s-\theta_r}\right]^\lambda \left[1-\left[1-\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{1/m}\right]^m\right]^2 \quad \textbf{(8)}$$

where $K_s$ is the saturated hydraulic conductivity (m/s), $\theta$ the volumetric soil water content ($m^3/m^3$), $\theta_s$ the saturated water content ($m^3/m^3$) often taken equal to the soil porosity, $\theta_r$ is residual water content ($m^3/m^3$), and the parameters $\alpha$ ($m^{-1}$), $n$, $m$, and $\lambda$ are empirical constants. As it may be assumed that $m=1-1/n$, the number of parameters needed to describe the water retention and hydraulic conductivity as a function of soil water pressure $h$ totals six: $K_s$, $\theta_s$, $\theta_r$, $n$, $\lambda$, and $\alpha$. The parameter values can be determined from measured $\theta$-$h$ and $K-h$ data pairs using non-linear curve fitting programs available in statistical software packages, spreadsheets, or by the optimization software package RETC.[30] Several authors present representative values of these parameters for a wide range of soil types.[31,32] These data bases frequently will make it possible to derive these quantitative parameters from qualitative soil descriptions in mine field reports.

### 2.3. Soil Dielectric Constant

The dielectric constant of a soil layer depends on the soil texture and the amount of water present in the soil. The dielectric constant of water at microwave frequencies is approximately 80, compared to 3 to 5 for dry soils.[33] It has been studied in different soils at frequencies from 1 MHz to 10 GHz[34], from 0.1 to 26 Ghz[35], from 1 MHz to 1 Ghz[6], and from 1 to 50 MHz.[36] Generally, these studies reveal that the relationship between dielectric constant and volumetric water content is almost independent of soil type. We will use an inverse of the calibration curve[6] to obtain estimates of dielectric constants from simulated soil water contents around land mines:

$$\epsilon = 3.03+9.3\times\theta+146\times\theta^2-76.7\times\theta^3 \quad \textbf{(9)}$$

where $\epsilon$ is the soil dielectric constant and $\theta$ is volumetric water content ($m^3/m^3$).

## 3. MATERIALS AND METHODS

From the many regions with a landmine problem we selected two with completely different climates: Kuwait with an arid desert climate and Bosnia with a humid temperate climate. Using one year of weather data from each location we modeled the temporally variable water distribution around an anti-tank mine in two different soil types. In this manner we can evaluate the effect of climate as well as soil type on water distributions around landmines.

The simulations have been conducted with the HYDRUS-2D package of the U.S. Salinity Laboratory at Riverside, California, which is a Microsoft Windows based modeling environment for analysis of water flow and solute transport in variably saturated porous media.[37] It includes a finite element model for simulating two-dimensional water and solute movement in variably saturated media. The program numerically solves a two-dimensional version of Eq. [6] including saturated and non-saturated conditions. For the landmine problem we used a quasi three-dimensional region exhibiting radial symmetry about the vertical axis. The flow equations are solved numerically using Galerkin-type linear finite element schemes. The model includes a mesh generator.

We have simulated water flow in a soil cylinder with a radius of 2 m and depth 2 m. The anti-tank mine was placed in the center of the cylinder with its bottom at a depth of .23 m. The height of the mine is about 0.08 m, its diameter 0.3 m. The lay-out used for the simulations is presented in Figure 1. The top boundary condition of the soil cylinder is determined by the atmospheric condition expressed as daily precipitation and potential evapotranspiration values. The bottom boundary condition is one of free drainage. The initial condition is a uniform soil water pressure in the entire soil profile of -1 m. The HYDRUS-2D model was used to simulate water movement during two years: the first year has not been used for the analysis in order to give the model time to adjust its initial condition to the atmospheric boundary conditions.

During the simulations we monitored soil water content at four observation points: x1 at depth 0.13 m and 0.02 m above the mine at a distance of 0.02 m from its center, x2 at depth 0.25 m and 0.02 m below the mine at a distance of 0.02 m from its center, x3 at a distance of 1 m from the center at the same depth as the observation point above the mine, x4 at a distance of 1 m from the center at the same depth as the observation point below the mine (Figure 1). The latter two points are so far away from the mine that the mine doesn’t interfere with water movement at those locations.

**Figure 1.** Layout for the simulation of water distributions around landmines with four observation points x1, x2, x3, x4.

Daily precipitation and potential evapotranspiration rates (cm/day) during the years 1987-1993 in Bosnia and Kuwait are presented in Figure 2. The straight horizontal line in the evapotranspiration figure for Kuwait indicates that no data were taken during the Gulf War. The mean annual precipitation and mean annual potential evapotranspiration for Bosnia are 926 and 815 mm; for Kuwait 81 and 2112 mm. Bosnia has a humid temperate climeate with an annual precipitation surplus while Kuwait has a hot dry climate where most of the precipitation that enters the soil will quickly evaporate. At both locations the daily evapotranspiration rates have a definite yearly cycle and don’t change much from one year to another. The daily precipitation values show a larger temporal variability but still a yearly cycle can be recognized. Periods with higher precipitation tend to coincide with periods

**Figure 2**. Daily precipitation and potential evapotranspiration values in Bosnia (1987-1993) and Kuwait (1987-1993). No data were taken at Kuwait from August 1990 to June 1991.

of lower potential evapotranspiration. Since the soil water distributions near the soil surface respond relatively quickly to weather events with response times in the order of days or weeks and annual weather patterns tend to be similar from year to year, soil moisture regimes around landmines are analyzed in this first study on the basis of our results for calendar year 1988. It takes about 3 hours to simulate one year of water movement on a 350 Mhz Pentium PC. In future studies we will also include weather variability between years since the precipitation data from Kuwait show large differences from one year to another.

We have selected a loam and loamy sand for the simulations. The Van Genuchten parameters used to characterize the water retention curves and unsaturated hydraulic conductivity curves according to Eqs. [7] and [8] are presented in Table 1.

Table 1. Van Genuchten parameters for loam and loamy sand.

| | Van Genuchten Parameters | | | | |
|---|---|---|---|---|---|
| | Residual Water Content | Saturated Water Content | Alpha | n | Saturated Hydraulic Conductivity |
| Soil Type | $cm^3/cm^3$ | $cm^3/cm^3$ | $cm^{-1}$ | - | cm/day |
| Loam | 0.078 | 0.43 | 0.036 | 1.56 | 24.96 |
| Loamy Sand | 0.057 | 0.41 | 0.124 | 2.28 | 350.20 |

## 4. RESULTS AND DISCUSSION

### 4.1. Effect of Soil and Climate on Soil Water Distributions

Figure 3 presents soil water content changes during the year 1988 in Bosnia and Kuwait in loam and loamy sand soils without vegetation. The water contents presented are taken at observation points x3 and x4 that are away from the landmine at depths of 0.13 and 0.25 m, respectively. These water contents are representative for soils without landmines. In Kuwait the loam and loamy sand have mean soil water contents of about 16 and 7 volume percent, respectively; in Bosnia, the mean water contents are higher with means of 30 and 14 volume percent in the loam and loamy sand. The difference in water content between Kuwait and Bosnia is larger in the finer textured loam soil than in the coarser textured loamy sand. For example, the precipitation in early 1988 resulted in water contents in the loamy sand in Kuwait that are similar to those found under the wetter conditions of Bosnia. Yet, the same amount of precipitation in the loam soil in Kuwait only resulted in water contents similar to those found during a dry spell in Bosnia. This demonstrates that soil water content regimes depend on the interaction between climate and soil characteristics.

**Figure 3**. Soil water content changes during 1988 at observation points x3 (0.13 m) and x4 (0.25 m) in a Loam and Loamy Sand in Kuwait and Bosnia.

The data in Figure 3 clearly illustrate that soil water content and, thus, soil dielectric constants depend to a large extend on climate and soil type. In most climates soil water contents near the soil surface will span the full range from wet to dry, but the frequency of these occurrences are determined by the climate. For example, at 0.13 m depth the loam in Kuwait does reach a water content of 24 volume percent during a few days while this water content is present most of the year in Bosnia loam. The water content simulations also demonstrate that worldwide soil moisture regimes can be predicted where soil maps and meteorological data are available.

Using Eq. [9] with the simulated soil water contents indicates that the dielectric constant in Kuwait varied from about 4 to 8 in the loamy sand and from 8 to 14 in the loam. In Bosnia the higher water contents resulted in dielectric constants from 4 to 12 in the loamy sand and from 9 to 50 in the loam.

### 4.2. Effect of Landmines on Soil Water Distribution

The literature presents a number of theoretical and experimental studies dealing with the effects of buried objects such as stones on soil water distribution and movement. These investigations point out that water contents above and below a stone can either be more or less than at the same depth away from the stone. The same observations can be made in our simulations. For example, Figure 4 shows soil water content distributions near the center of a landmine in a loam in Kuwait. On day 15 the water content above the mine is higher than away from it while below the mine the water content is less than away from it. However, after day 30 the water distribution is completely reversed. Now the water content above the mine is less than away from it while below the mine the water content is higher. The latter and former water content distribution coincide, respectively, with a wet and dry time span (see Figure 2). Figure 4 is evidence that the landmine does affect soil water content distributions around it in a very dynamic way which depends on the interaction between soil and climate factors.

**Figure 4**. Soil water content versus depth at the center of the mine (r=0.03 m) and away from it (r=1.1 m) under dry conditions (day 215 in Kuwait and Bosnia) and wet conditions (day 10 in Kuwait and day 235 in Bosnia).

This complex behavior is further explored in Figure 5 where soil water content differences between “the center of the mine” and “far away from it” are plotted against time for both soils in Kuwait and Bosnia. The four plots look quite different but the common denominator is that during periods of major precipitation the water content above the mine is higher than away from it while the water content below the mine is lower. A correlation exists between the amount of precipitation and the absolute water content differences above and below the mine. This explains why the water content differences in Bosnia are higher than those in Kuwait. During dry spells the water content distributions around a landmine tend to reverse: the soil below the mine tends to be wetter than the soil at the same depth away from the mine, while the soil above the mine tends to be drier than away from it. This effect is best observed in the loam soil in Kuwait. After day 40 when the effects of the rain of day 6 have ebbed away, the soil below the mine becomes wetter and above the mine drier than at similar depths away from the mine. The small amount of precipitation on day 64 could not reverse this pattern. The loamy sand in Kuwait shows a similar pattern but less pronounced. In the wetter climate of Bosnia the water distribution around the mine in a loam soils shows clearly a reverse during dry spells while in the loamy sand no such reverse takes place.

**Figure 5**. Water content at observation point x1 minus water content at observation point x3 (0.13 m) and water content at observation point x2 minus water content at observation point x4 (0.25 m).

Figure 5 is evidence that the landmine does affect the soil water distribution around it in a complex manner. At some times water contents above and below the mine are higher than at similar depths away from the mine while at other times those water contents are lower.

**4.3. Effect of Soil and Climate on Distribution of Soil Dielectric Constants**

Some mine detection methods based on high frequency electromagnetics such as radar sensors detect the soil dielectric constants of the landmine and the soil. Since a dry soil and a landmine both have a dielectric constant of about 2 such sensors cannot detect mines under dry conditions for lack of a contrast in dielectric constant. When the soil becomes wet the contrast increases and detection becomes easier. Using Eq. [9] the water contents observed above the landmine at observation points x1 and x4 (see Figure 1) have been converted into soil dielectric constants. Figure 6 presents the frequency of occurrence of the dielectric constant in the loam and loamy sand under Kuwait and Bosnia weather conditions. In Kuwait soil dielectric constants of 5 in the loamy sand to 7 in the loam are most common. This means that the dielectric constants exceeded these values only a few days in 1983. In Bosnia, the wetter climate results in higher values of dielectric constants but also here the values in the loamy sand are lower than in the loam.

Assuming that a radar sensor needs a dielectric contrast of at least 7 to detect a mine, chances are that such a sensor will fail in loamy sands in Kuwait most of the time since only during a few days does the dielectric constant exceed the threshold value of 7. On the other hand, the same sensor will work most of the time in loamy sands of Bosnia since the wetter climate results in higher dielectric constants. The same sensor will also be functional most of the time in loams of Kuwait and all the time in loams of Bosnia.

**Figure 6**. Frequency of dielectric constant close to the mine (r=0.03 m) and away from it (r=1.1 m).

## 5. CONCLUSIONS

The simulation results presented in this study indicate that soil water distributions are highly variable in time as well as space and depend in a complex manner on weather conditions and soil type. It also has been shown that the landmine itself influences soil water content distributions.

The direct relationship between water content and soil dielectric constant expressed in Eq. [9] causes the variability of soil dielectric constants to be similar to soil water content variability. Given the multitude of studies on spatial and temporal variability of soil water, it is possible to reliably assess the spatial and temporal variability of soil dielectric constants using existing variably saturated water flow models.

This study shows how soil water content distributions near landmines and away from them can be predicted anywhere in the world where soil maps and meteorological data are available. Since soil water content is an important environmental variable that affects many sensors, the simulation of soil water content distributions is useful for the determination of windows of opportunities for mine detection.

The simulations presented here dealt with homogeneous soils without vegetation. Future research will be more realistic and will include the effects of soil spatial variability and vegetation.

## ACKNOWLEDGMENT

This work is funded by a grant from the Army Research Office (Project 38830-EL-LMD). The authors like to thank Dr. Russell S. Harmon, Senior Program Manager at the Army Research Office, for his valuable advise and support.

## REFERENCES

1. Bruschini, C. and B. Gros. 1997. A survey of current sensor technology research for the detection of landmines. Intern. Workshop on Sustainable Humanitarian Demining, Zagreb, Croatia. 29 Sept. - 1 Oct..

2. Rouhi, A.M. 1997. Land mines: horrors begging for solutions. Chemical & Engineering News, March 10.

3. Strada, G. 1996. The horror of land mines. Scientific American May:40-45.

4. Rhoades, J.D. 1993. Electrical conductivity methods for measuring and mapping soil salinity. *In*: D. Sparks (ed.), Advances in Agronomy. Vol. 49:201-251.

5. Sheets, K.R. and Hendrickx, J.M.H. 1995. Noninvasive soil water content measurement using electromagnetic induction. Water Resour. Res. 31; 2401-2409.

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

7. Van Wijk, W.R. (ed.). 1963. Physics of plant environment, North-Holland Publ., Amsterdam.

8. Hendrickx, J.M.H. and G. Walker. 1997. Recharge from precipitation. Chapter 2. *In*. I. Simmers (ed.), Recharge of phreatic aquifers in (semi)-arid areas. Balkema, Rotterdam, The Netherlands.

9. Hillel, D. 1980. Fundamentals of soil physics. Academic Press, Inc., London; 413 pp.

10. Van Keulen, H. & De Wolf, J. (eds). 1986: *Modeling of agricultural crop production, weather, soils and crops*. PUDOC, Wageningen, The Netherlands; 477 pp.

11. Bouwer, H. & Rice, R.C. 1984. Hydraulic properties of stony vadose zones. Ground Water, 22; 696-705.

12. Fennemore G.G. and A.W. Warrick. 1997. Simulation of unsaturated water flow around obstructions three-dimensional Rankine bodies. Adv. Water Resour. 20:15-22.

13. Hendrickx, J.M.H., Khan, S., Bannink, M.H., Birch, D. & Kidd, C. 1991. Numerical analysis of groundwater recharge through stony soils using limited data. J. Hydrol*.,* 127; 173-192.

14. Knight, J.H. and J.R. Philip. 1989. The seepage exclusion problem for spherical cavities. Water Resour. Res. 25:29-37.

15. Philip, J.R. 1990. Some general results on the seepage exclusion problem. Water Resour. Res. 26:369-377.

16. Subia, S.R., Ingber, M.S. & Martinez, M.J. 1994. A three-dimensional boundary element method for steady unsaturated quasilinear flow in porous media. Water Resour. Res., 30; 2097-2104.

17. Warrick, A.W. and G.G. Fennemore. 1995. Unsaturated water flow around obstructions simulated by two-dimensional Rankine bodies. Adv. Water Resour. 18:375-382.

18. Campbell, G.S. 1985. Soil physics with basic. Transport models for soil-plant systems. Elsevier, New York, USA; 150 pp.

19. Hanks, R.J. & Ashcroft, G.L. 1986. Applied soil physics. Advanced Series in Agricultural Sciences 8. Springer-Verlag, New York, USA; 159 pp.

20. Jury, W.A., Gardner, W.R. & Gardner, W.H. 1991. Soil physics. John Wiley and Sons, New York, USA; 328 pp.

21. Koorevaar, P., Menelik, G. & Dirksen, C. 1983. Elements of soil physics. Elsevier, New York, USA; 230 pp.

22. Bear, J. 1972. Dynamics of fluids in porous media. Dover Publications, Inc., New York, USA; 764 pp.

23. Childs, E.C. 1969. The physics of soil water phenomena. John Wiley and Sons, New York, USA

24. Dullien, F.A.L. 1992. Porous media: Fluid transport and pore structure. Academic Press, New York, USA; 574 pp.

25. Hendrickx, J.M.H. 1990. Determination of hydraulic soil properties. In: M.G. Anderson & T.P. Burt (eds), Process studies in hillslope hydrology. Chapter 3; 43-92.

26. Klute, A. (ed.). 1986. Methods of soil analysis, Part 1, Physical and Mineralogical methods (2nd ed.), Agronomy 9. Soil Science Society of America, Madison, Wisconsin, USA.

27. Van Genuchten, M.Th., Leij, F.J. & Lund, L.J. (eds). 1992. Indirect methods for estimating the hydraulic properties of unsaturated soils. Proceedings of the International Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils. Riverside, California, October 11-13, 1989. U.S. Salinity Laboratory, Agricultural Research Service, U.S. Dept. of Agriculture, Riverside, California, USA; 718 pp.

28. Wierenga, P.J., Young, M.H., Gee, G.W., Hills, R.G., Kincaid, C.T., Nicholson, T.J. & Cady, R.E. 1993. Soil characterization methods for unsaturated low-level waste sites. Report NUREG/CR-5988, PNL-8480, U.S. Nuclear Regulatory Commission, Washington, DC, USA; 141 pp.

29. Van Genuchten, M.Th. 1980. A closed-form equation for predicting the hydraulic properties of unsaturated soils. Soil Sci. Soc. Am. J. 44:892-898.

30. Van Genuchten, M.Th., F.J. Leij, and S.R. Yates. 1991. The RETC code for quantifying the hydraulic functions of unsaturated soils. U.S. Salinity Laboratory, Agricultural Research Service, U.S. Dept. of Agriculture, Riverside, California, USA.

31. Carsel, R.F. & Parrish, R.S. 1988: Developing joint probability distributions of soil water retention characteristics. *Water Resour. Res.*, 24; 755-769.

32. Leij, F.J., Alves, W.J., Van Genuchten, M. Th. & Williams, J.R. 1996: *The UNSODA unsaturated soil hydraulic database. User's manual version 1.0*. United States Environmental Protection Agency, IAG-DW112933934; 100 pp.

33. Schmugge, T.J. 1985. Remote sensing of soil moisture. Pp. 101-124. John Wiley, New York.

34. Brisco, B., T.J. Pultz, R.J. Brown, G.C. Topp, M.A. Hares, and W.D. Zebchuk, 1992. Soil moisture measurement using portable dielectric probes and time domain reflectometry. Water Resour. Res. 28:1339-1346.

35. Hoekstra, P. and A. Delaney. 1974. Dielectric properties of soils at UHF and microwave frequencies. J. of Geophysical Res. 79:1699-1708.

36. Campbell, J.E. 1990. Dielectric properties and influence of conductivity in soils at one to fifty Megaherz. Soil Sci. Soc. Am. J. 54:332-341.

37. Šimůnek, J., Vogel, T. & Van Genuchten, M.Th. 1994: *The SWMS-2D code for simulating water flow and solute transport in two-dimensional variably saturated media*. V.1.2. Research Rep. No. 132, U.S. Salinity Laboratory, Agricultural Research Service, U.S. Dept. of Agriculture, Riverside, California, USA; 196 pp.

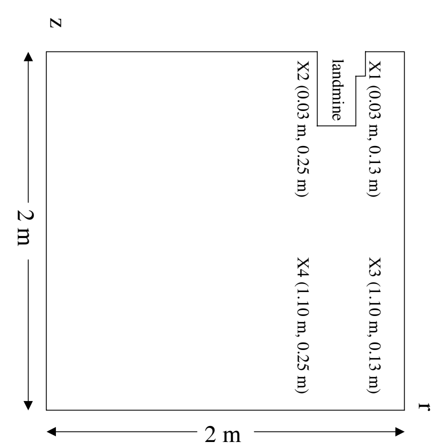


Figure 1: Layout for the simulation of water distributions around landmines with four observation points x1, x2, x3, x4.

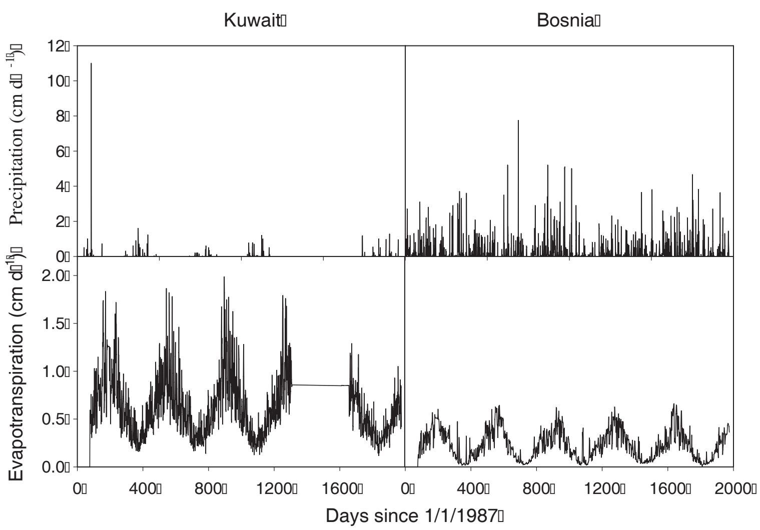


Figure 2: Daily precipitation and potential evapotranspration values in Bosnia (1987–1993) and Kuwait (1987–1993). No date were taken at Kuwait from August 1990 to June 1991.

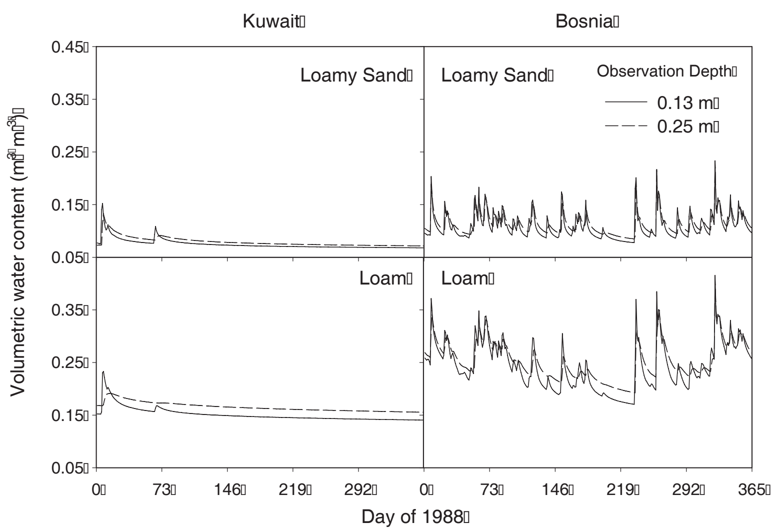


Figure 3: Soil water content changes during 1988 at observations points x3 (0.13 m) and x4 (0.25 m) in a Loam and Loamy Sand in Kuwait and Bosnia.

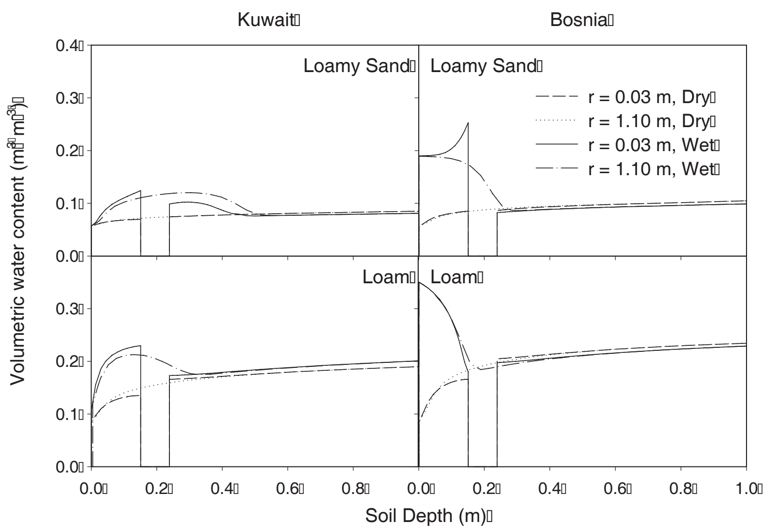


Figure 4: Soil water content versus depth at the center of the mine (r=0.03 m) and away from it (r=1.1 m) under dry conditions (day 215 in Kuwait and Bosnia) and wet conditions (day 10 in Kuwait and day 235 in Bosnia).

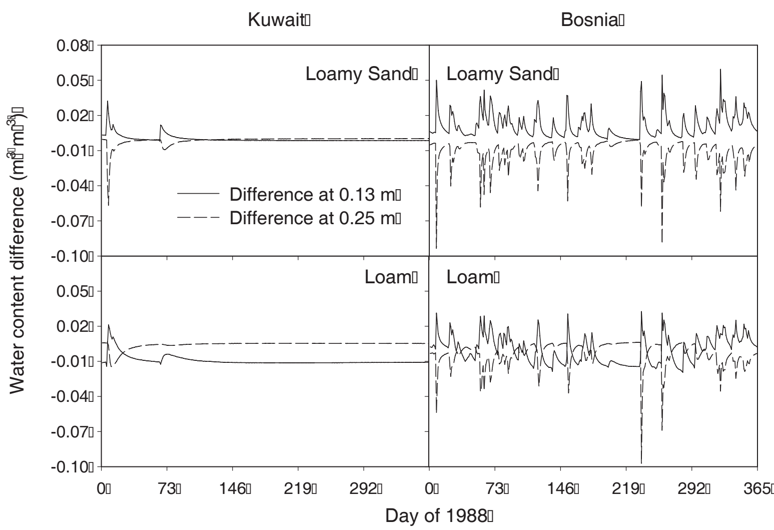


Figure 5: Water content at observation point x1 minus water content at observations point x3 (0.13 m) and water content at observation point x2 minus water content at observation point x4 (0.25 m).

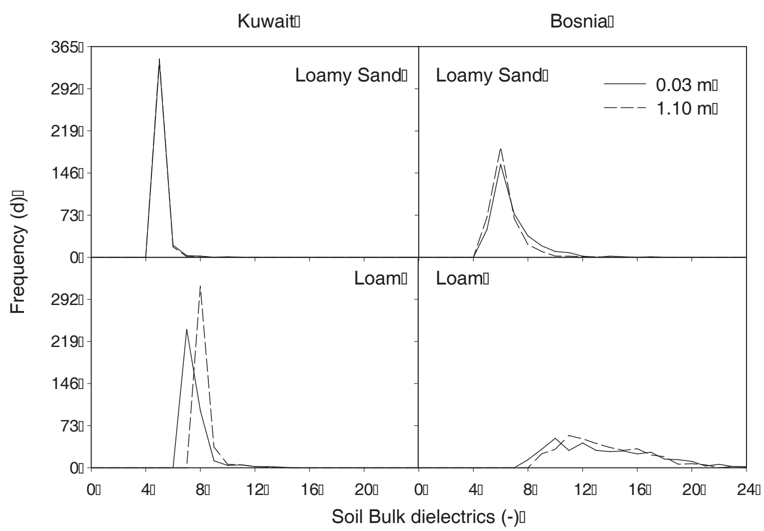


Figure 6: Frequency of dielectric constant close to the mine (r=0.03 m) and away from it (r=1.1 m).