Contribution of Soil Physics to Sustainability

Qudsia Gani

Department of Physics, Govt. College for Women
Cluster University M.A. Road Srinagar, INDIA-190001

Corresponding author: qudsiagani6@gmail.com

Abstract
The interaction of soil with other entities such as atmosphere, water or even plants and animals, has been significantly affected due to human stewardship. Agricultural production, design of drainage and irrigation as well as the construction of structures, depend on various properties of soil such as bulk density, specific gravity, water holding capacity, porosity, electrical conductivity, heat capacity, temperature, alkalinity, organic matter content etc. Soils are foundational to many essential ecosystems besides providing the food, energy and water. Soil degradation is therefore an issue of huge urgency to humanity to sustainably meet the needs of the rising world population, estimated to reach 9 billion by 2050, as per the world population prospects, WPP highlights of 2019. In this context, Soil Physics has been making great contribution to sustainable world development by way of soil protecting measures, since its establishment as a scientific discipline in the early 20th century. This also requires scientists across various disciplines to collaborate, to obtain the desired results.

Keywords: Soil texture, irrigation, drainage, crop management, ecology, systems approach, interdisciplinary.

Introduction
Soil physics is the application of principles of physics to address practical problems in agriculture and ecosystems. However, more broadly, it also involves the disciplines like physical chemistry, engineering, and meteorology. The late professor R D Miller of Cornell University of Ithaca is known to be the founding father of `Soil Physics'.
Soil physics describes the dynamics of physical components of soil and their phases such as solid and fluids i.e liquids and gases. This discipline is quantitative and mathematical in nature and is therefore useful to study the state and transport of matter and energy in the soil.
Soil is composed of sand, silt, clay and organic matter with airspaces in between. These small particles lump together to form peds, or what we call aggregates. The shape and size of these peds determine the soil texture and structure. Based on well known Stoke's law in

physics (Ranjan and Rao, 2020) an instrument namely Hydrometer is designed to calculate the size of soil particles from the speed at which they settle out of suspension from a liquid. This sedimentation method is familiar to all geotechnical laboratories. A typical Hydrometer (Bendick, 2011) is shown in the (**Figure 1**) as shown below.

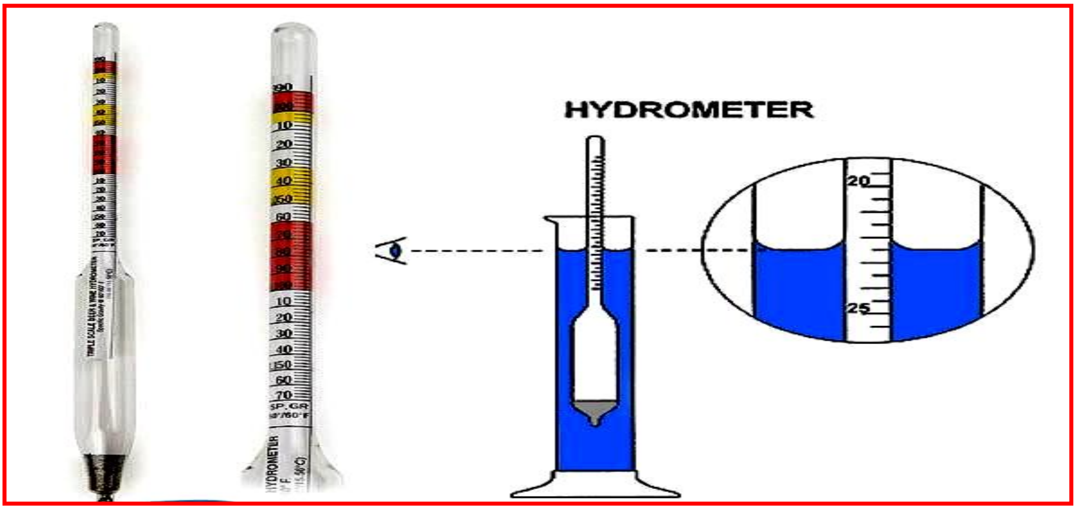

Figure 1: An overview of hydrometer

Being porous, soils also have the ability to store greenhouse gases, but they can also release them. Whether soils are a sink, storing greenhouse gases or a source, releasing greenhouse gases depends on how the soil is managed. A number of efforts are being carried out globally to make soil physics applicable to the analysis of the physical behaviour of field soils. One such method is the use of isotopes and radiation techniques (Reichardt, 1983). As for instance, Nitrogen-15 is used as a tracer in fertilizer studies. Being an essential plant nutrient, it is used to determine the fertilizer use efficiency of crops. Similarly, neutron probe is used in field-water balances. A typical neutron probe consists of a pellet of americium-241 and beryllium (Robock, 2015). The decay of the americium produces alpha particles which collide with the light beryllium nuclei, producing fast moving neutrons which further undergo collisions with hydrogen nuclei present in the soil sample losing much of their energy. The rate of slow neutrons returning to the probe gives an estimate of the amount of hydrogen present in the soil. Since water molecule contains two atoms of hydrogen, this gives a fair idea of the moisture content of soil.

Temperature is another important factor determining biological activity within the soil. How soil conducts heat determines how water evaporates from soil, and this rate is also closely linked with the water content of soil.

Soils at different locations are different and diverse, since these are also moved by water, as there are hills and depressions that water needs to move through until it gets to the streams or reaches the ground. The soil below the ground water level is said to be saturated with a hydrostatic pressure greater than the atmospheric pressure, thus having a positive pressure potential whileas the water which rises through the capillary action has a negative pressure potential with reference to the surface or atmospheric pressure. Soil-water potential is a dynamic property of the soil, generally known as matric potential. It is expressed as

$$\Psi_m = -mgh$$

$$\Psi_m = -\rho_m gh \quad \text{per unit volume}$$

$$\text{and} \quad \Psi_m = -h \quad \text{per unit weight}$$

The equations of capillarity do not suffice to describe the hydrodynamics in soil. This is because soil is not simply a bundle of capillaries but it is also characterised by the property of adsorption due to which hydration envelopes get formed over the particle surfaces. Water in an unsaturated soil is subject to capillarity and adsorption, which combine to produce the matric potential (Harttnann, 2001). It is measured using a tensiometer (Rawls *et al.*, 1993), described in (**Figure 2**) as follows.).

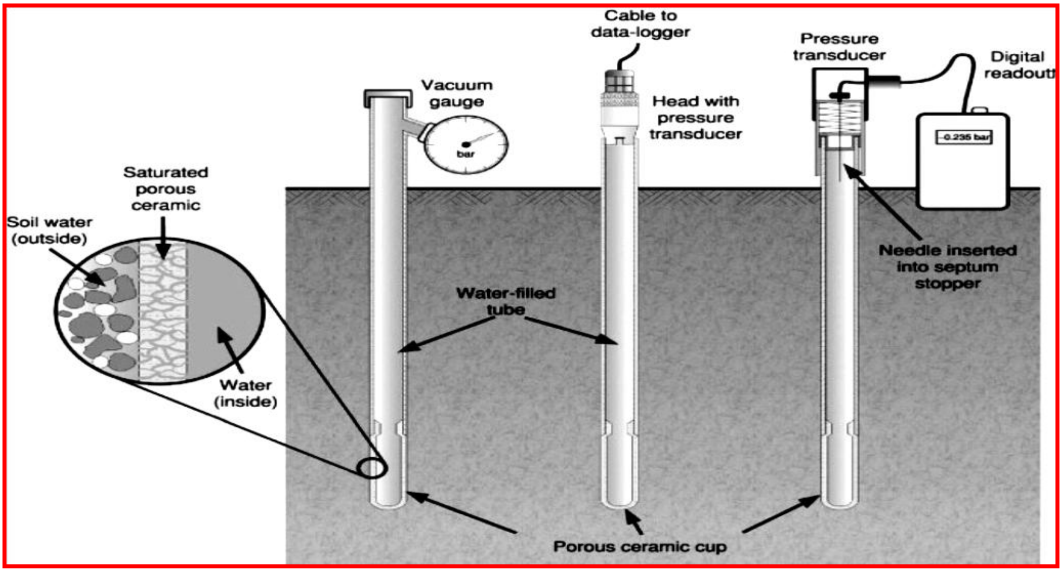

Figure 2: An overview of tensiometer

Tensiometer is designed to perform highly accurate and automatic measurements of surface tension, interfacial tension, critical micelle concentration, CMC and contact angle measurement on solids, fibers, and powders. Similarly, various types of soil integrated sensors such as optical, spectroscopic and micro-electromechanical are used to determine the soil quality in terms of its components, mineral content, pH, temperature, moisture etc. The mineral make up and the degree of compaction of soil determine its bulk density. It is inversely related to soil porosity and is measured as

$$\rho_s = M_s / V_s$$

where M_s is the mass of dry or wet soil and V_s the whole volume of soil. As for instance, the bulk density of dry soil is half the density of Quartz which is around 2.65 g/cm^3. Bulk density of soil at a region on earth is also related to the velocity of P & S seismic waves. These have been quantified with Gardner's relation (Gardner *et al.*, 1974) given by

$$\rho_s = \alpha \, VP^{\beta}$$

where α and β are geological constants and VP is the velocity of P waves. The higher the soil density, the faster is the velocity. This relation is quite popular in hydrocarbon exploration since it provides information about the lithology from velocity intervals obtained from seismic data. Another important parameter is the mass wetness W. It is the ratio of mass of water to mass of dry soil in a given sample. The soil water content θ is given by the product of mass wetness and bulk density of dry soil i.e

$$\theta = W \times \rho_s$$

Agricultural production depends mainly on the water holding and transmission capacities of the soil. It is also severely affected by the varying degrees of salt content of soils. Accordingly, soils are classified as saline or sodic/saline depending on their alkalinity, and are capable of supporting very little vegetative growth. These soils have a high electrical conductivity and are identified by spotted crop growth.

Thus soil physicists study many different themes and interactions involving soil as a finite natural resource; its formation and classification; mapping of it's physical, chemical, biological, and fertility properties in relation to it's use and management; the transfer of energy from one place to another, the movement of water through soil and plants, study of gas emissions and so on. Others include finding out what happens to soil when it is tilled, and what happens if the soils become too salty to use.

Global issues of soil management

Although the commercialisation of agriculture has significantly contributed to the GDP of many developing countries in Asia but at the same time it has widened the gap between food demand and supply. Some of the cash crops can be water intensive and may lead to water scarcity. As for instance, India being one of the largest producers of sugarcane in the world and given the fact that it takes 1500-3000 litres of water to produce one kilogram of sugarcane, it may not be sustainable in the long run. The focus on cash crops has also resulted in a sharp increase in the use of herbicides and pesticides. The global pesticide industry is currently estimated at $ 70 billion and is expected to reach $ 90.1 billion by 2022 (OECD/FAO, 2021), China is at the top the list of pesticide users, having an annual pesticide consumption of 1,806,000 metric tonnes whileas India is in tenth place with the usage of 40,000 metric tonnes. At the global level, a growth rate of 6.9 % in the use of pesticides has been estimated between 2014 and 2020 with Asia-Pacific having the highest growth rate in pesticide use in future. The largest impact by far, of this practice is on biodiversity which is being sacrificed for the sake of short term financial benefits. Land degradation also affects severely the domains outside agriculture. It has implications for our environment, our landscapes and water quality as well as the energy sector and urban infrastructure. The economic cost of soil degradation in the USA is about US $ 44 billion per year and for the European Union, it is of the order of tens of billions of euros annually. The cost of land degradation in India is 2.54 % of it's GDP annually (Bhattacharyya *et.al.*, 2015). India aims to cover up this problem by 2030. However, according to a recent study of 2018, by a Delhi based think-tank namely “The Energy and Resource Institute" TERI, the government needs to speed up reclamation as the cost of land degradation may outstrip the cost of reclamation in 2030. Similarly, in another study of 2016 done by Space Applications Centre of the Indian Space Research Organisation ISRO, India has a geographic area of 328.72 million hectare out of which 96.4 million hectare, or 29.32 % of land area has undergone degradation. There is an urgent need to address these issues through an interdisciplinary approach, but at a more basic level we need to develop an objective, quantifiable, and precise concept based on scientific principles.

Solutions from soil physics

Soils are foundational to sustaining the food, energy, and water; popularly known as FEW systems (Shang *et al.*, 2018). Therefore it is critical to advance soil physics to improve the FEW supplies to the growing human population in a sustainable and resilient manner. Soil physics can be instrumental in developing proper land use and agricultural practices. However, due to cost constraint, direct use of field and laboratory measurements and remote sensing described in the previous section is done on a restricted scale. In that context, the concept of physical modeling of soil (Addiscott, 1993) comes very handy which is described in the following section.

Soil physical modeling

The physical modeling is executed using computers and is known as simulation. It is an interface between theory and experiment, used to evaluate the feasibility of a proposed experiment, analyse the collected data and samples and evaluate the systematic errors. Simulations are used in everything from nuclear physics to chemistry to economics to say, regulating the flow of traffic. Of course, the way these are operated or executed varies widely from one field to another. The use of simulations to model physical problems allows us to examine more complex systems than we otherwise can do. It is fairly simple to solve equations which describe the interactions between two atoms but solving the same set of equations for hundreds or thousands of atoms is not so easy. With the technique of simulations, a huge or a complex system can be sampled in a number of random configurations and that data can be used to describe the system as a whole. In order that the simulations could be accepted in the general community these have to mimic the experimental results. If the two data sets reconcile, then these have some credibility. In the last so many years, many numerical models involving physics phenomena such as electromagnetic induction, electrical resistivity tomography, and ground-penetrating radar have been calibrated to probe the processes on the sub-surfaces of soil. Soil modeling is useful to reasonably predict and explain vividly, the mechanisms in soil water management, crop production, and environmental protection. Some of the physical soil models currently in vogue are:

HYDRU-1D Model: It is related to hydrological modeling of the soil and hence the name. The software package consists of a one-dimensional finite element model (Simunek *et al.*, 2012). It requires a Microsoft Windows-based modeling environment for analysis. This model presents the the distribution of the pressure head, water content, water and solute fluxes, root water uptake, temperature and the concentration in the soil profile in the form of interactive-graphs at preselected times. The model is enabled for the analysis of the flow and transport of matter and energy across soils of non-uniform composition along horizontal, vertical or a generally inclined direction. In this model, there are provisions for linear equilibrium reactions between liquid and gaseous phases as well as for non-linear or non equilibrium reactions. This model has been widely used for soil research studies in China.

Water Erosion Prediction Project (WEPP) Model: This is also a simulation model built on the fundamentals of the mechanism of hydraulics and erosion (Han *et al.*, 2016). The model was prepared by a team of soil scientists and researchers in the United States and is widely used across the globe. It requires inputs about four important variables i.e, climate, topography, soil, and vegetation; and provides various types of outputs such as water balance, soil detachment and deposition especially along the slope, sediment delivery, and vegetation growth. The main interface for the model is a standalone downloadable Windows application that allows a user to simulate the profiles of hill slope and small watersheds and have full control over all model inputs.

Community Land Model: This model is a collaborative work of the scientists in the Terrestrial Sciences Section, TSS and the Climate and Global Dynamics Division, CGD at the National Center for Atmospheric Research, NCAR based in Boulder, Colorado State University, U. S. A (Lawrence *et al.,* 2019). This model quantifies concepts of ecological climatology to understand how natural and human changes in vegetation affect climate. The current version of the Community Land Model is CLM5. There is a long list of such models which have improved the efficacy of soil research.

According to Einstein, if we are given 60 minutes to solve a problem, we should spend 55 minutes in thinking if the right question has been asked. In other words, we need to build a problem to understand it's prognosis to be able to provide it a viable solution. Now, once a huge number of instruments and physical models are in place to properly identify the discrepancies in soil management, the solutions follow automatically. The need is to understand and be well guided by the results and outputs of these research tools to obtain what is desired.

Conclusions

The relation between science and society has changed profoundly with time. The prevailing trend is to engage scientific institutes with the broader public to value the scientific findings, and the legitimacy of science as a whole. One such arena is that of soil physics. The need to preserve soil and water has been well recognized. Agricultural practices and ecological trends are affected by physical properties of soil and vice-versa. Moreover, the frequency of natural disasters such as landslides and thunderstorms has added importance to integrate soil characteristics in predictive models of science. Soil physics research has grown considerably in the use of innovative lab sensors and soil databases (Boyan *et. al*., 2012). Also, an interdisciplinary approach such as intensive interaction of scientists with stakeholders and policymakers is necessary to maintain the vigor of this research which may otherwise get lost in general discussions only.

People, especially those involved in land use practices, can be a major asset in reversing a trend towards degradation. But for that, they need to be healthy and politically and economically motivated to care for the land.

References

Addiscott, T.M. 1993. Simulation modelling and soil behaviour, ***Geoderma***, **60**: 15-40

Bendick, J. 2011. Archimedes and the Door of Science, ***Literary Licensing***, **1**: 63-64

Bhattacharyya, R., Ghosh, B. N., Mishra, P. K., Mandal, B., Rao, C. S., Dibyendu Sarkar, D. Krishnendu Das, K., Anil, K. S., Lalitha M., Kuntal Mouli Hati, K. M. and Alan Joseph Franzluebbers, A. J. 2015. Soil Degradation in India: Challenges and Potential Solutions. ***Sustainability.* 7:** 15-25

Borrelli, P.,. Robinson, D.A, Fleischer L. R., Lugato, E., Ballabio, C., Alewell,C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V. 2017. An assessment of the global impact of 21st century land use change on soil erosion. ***Nature Communicatio***n. **8** , pp.1-13; 10.1038/s41467-017-02142-7.

Boyan, K., Mahmood, H. S. ; Quraishi, M. Z. ; Hoogmoed, W. B. ; Mouazen, A. M. ; Henten, E. J. van. 2012. Sensing Soil Properties in the Laboratory, In Situ, and On-Line, ***Advances in Agronomy*. 114**: 155-223

Gardner, L. W., Gardner, L. W., Gregory A. R. 1974. Formation velocity and density- the diagnostic basics for stratigraphic traps. ***Geophysics.*** 39: 770–780; http://dx.doi.org/10.1190/1.1440465

Han, F., Ren, L., Zhang, X., & Li, Z. 2016. The WEPP model application in a small watershed in the Loess Plateau. PLoS ONE, 11(3), e0148445. https://doi.org/ 10.1371/ journal. pone.0148445

Harttnann, R. 2001. ***College on Soil Physics***, Lecture notes on soil physics. [Laboratory of Soil Physics, Department of Soil Management and Soil Care, Faculty of Agricultural and Applied Biological Sciences, University Gent – Belgium; 66P.

Lawrence, D. M., Fisher, R. A., Koven, C. D., Oleson, K. W., Swenson, S. C., Bonan, G., Collier, N., Ghimire, B., van Kampenhout, L., Kennedy, D., Kluzek, E., Lawrence, P. J., Li, F., Li, H., Lombardozzi, D., Riley, W. J., Sacks, W. J., Shi, M., Vertenstein, M., … Zeng, X. 2019. The Community Land Model Version 5: description of new features, benchmarking, and impact of forcing uncertainty. ***J Adv Model Earth Syst,*** 11(12), 4245–4287. https://doi.org/10.1029/2018MS 001583

OECD/FAO. 2021. OECD-FAO Agricultural Outlook 2021-2030, OECD Publishing, Paris, https://doi.org/10.1787/19428846-en. ISBN 978-92-64-43607-7 (print) and ISBN 978-92-64-98957-3 (pdf)

Ranjan, G. and Rao, A. S. 2020. Basic and applied soil mechanics, (3rd edn.) New Age International Publishers, New Delhi; ISBN: 81-224-1223-8. 153pp

Rawls, W.J., Ahuja, L.R., Brakensiek, D.L., and Shirmohammadi, A. 1993. Infiltration and soil water movement, in Maidment, D.R., Ed., Handbook of hydrology, New York, NY, USA, McGraw-Hill, **5:** 1–51.

Reichardt, K. 1983. Soil physics and agricultural production, IAEA Bulletin **25 (3)**: 3-10

Robock, A. 2015. Hydrology, floods and droughts in Encyclopedia of Atmospheric Sciences, **2**:15-20

Sartori, M., Philippidis, G., Ferrari, E., Borrelli, P., Lugato, E., Montanarella, L., Panagos, P. 2019. A linkage between the biophysical and the economic: assessing the global market impacts of soil erosion. ***Land Use Policy***. **86:** 299–331

Shang, J., Zhu, Q and Zhang, W. 2018. Advancing Soil Physics for Securing Food, Water, Soil and Ecosystem Services, ***Vadose Zone Journal*** . **17(1):** 1-7

Simunek, J.,Genuchten, M. Th. Van., Sejna, M. 2012. HYDRUS: MODEL USE, CALIBRATION, AND VALIDATION, ***American Society of Agricultural and Biological Engineers***. **58(6):** 1637-1660; ISSN 2151-0032